

Phantom

# Tailored Arrivals

## (Procedure Development & Implementation)

### **Rob Mead**

Lead Engineer  
Phantom Works Advanced ATM  
The Boeing Company



### **Rich Coppenbarger**

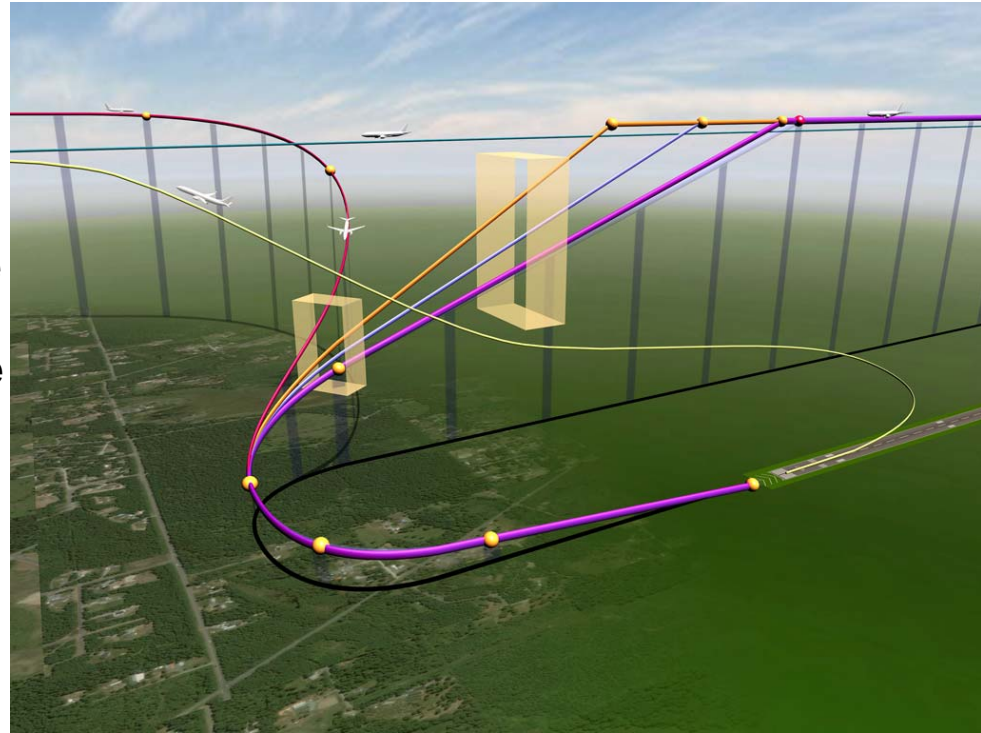
Principal Investigator, EDA/TA  
Automation Concepts Research Branch  
NASA Ames Research Center

- ✈ Overview
- ✈ Oceanic Tailored Arrivals (OTA) SFO Trials
- ✈ En Route Descent Advisor (EDA) - Status and Plans
- ✈ Next Steps with US Tailored Arrivals
  - OTA operational deployment at SFO
  - OTA developmental demonstration at Miami (AIRE)

# Tailored Arrivals

Engineering, Operations & Technology | Phantom Works

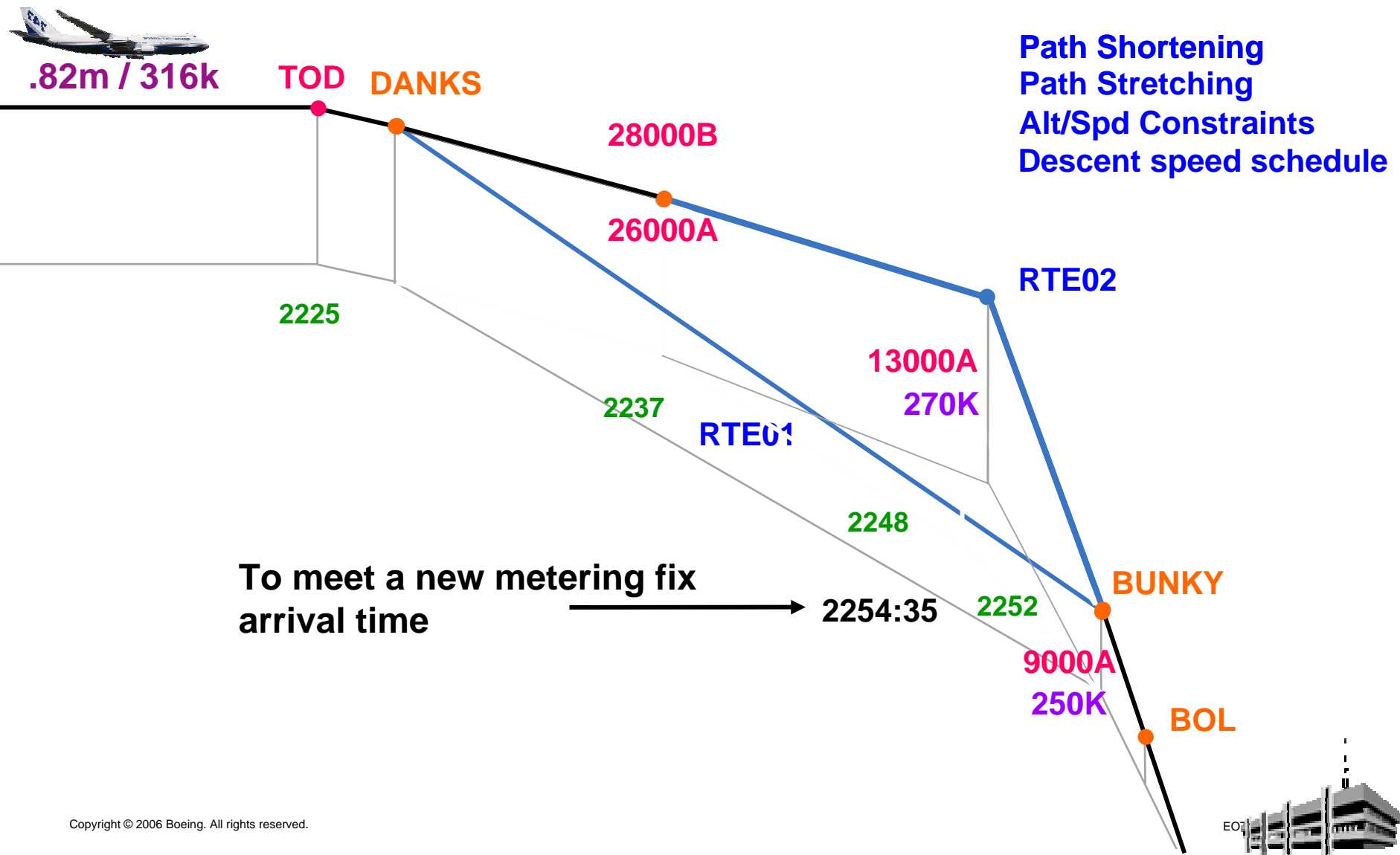
- **Tailored arrival — key features:**
  - Continuous descent from cruise altitude to touchdown
  - Tailored for traffic, environment, ...
  - Controller-to-aircraft datalink\*
  - Definition of flight path in both time and space (4D)
  - Cleared flight path through multiple centers
  - Currently available a/c capabilities
- **Benefits:**
  - 100 to 400 kg less fuel per flight
  - Flight duration reduced several min
  - Dramatically reduced VHF voice communication
  - Overall efficiency improved
  - Important step toward modernization of ATM



\*If ATC does not have data link, tailored arrivals can still be achieved by using pre-negotiated set of standard arrival procedures pre-stored in FMS.

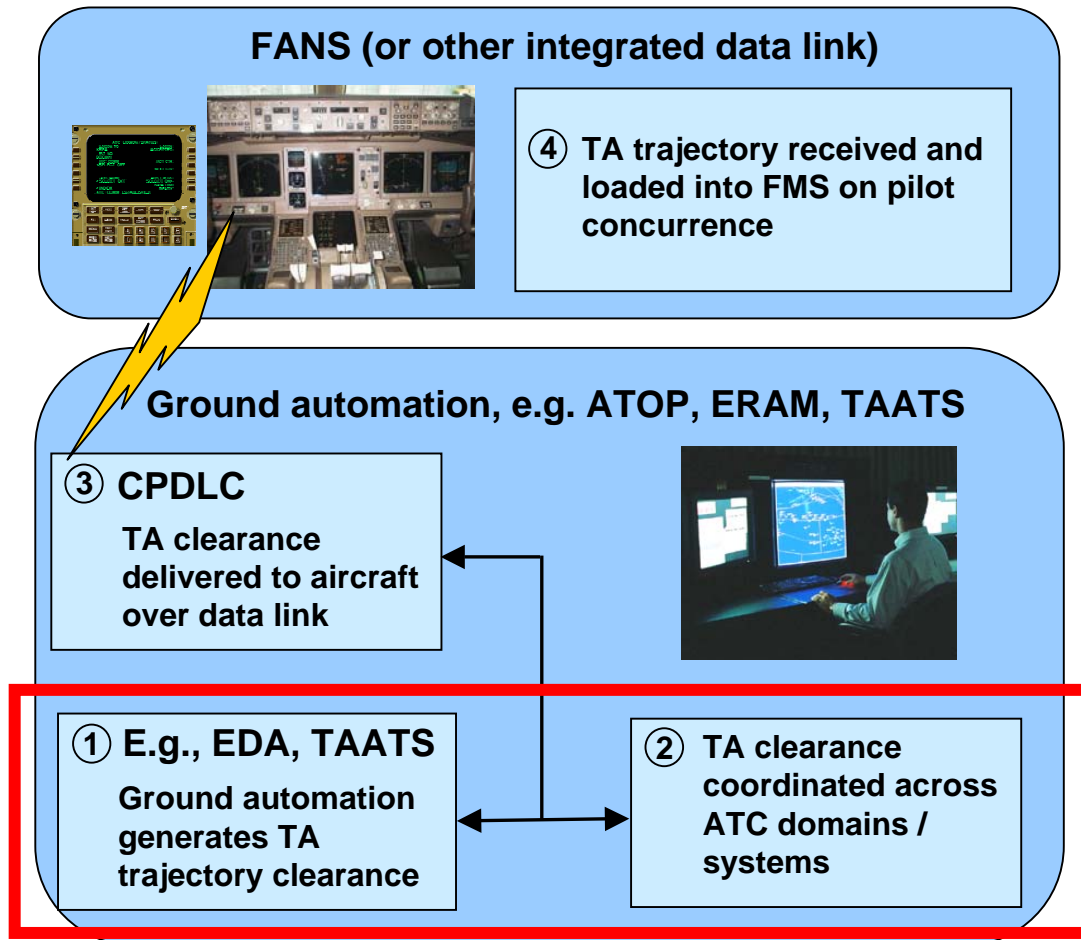
# Tailored Arrival Components

Engineering, Operations & Technology | Phantom Works



# What we need (end-state) ...

Engineering, Operations & Technology | Phantom Works

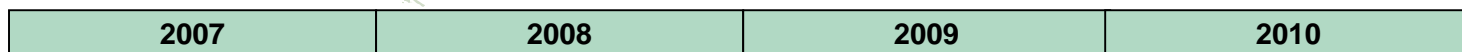


- ⑤ TA trajectory flown with FMS
- ⑥ Aircraft downlinks ETA information (at waypoints) along with other useful parameters for ATC trajectory confirmation and tuning
- ⑦ TA procedure broken off if trajectory cannot be continued for any reason

**The key hurdles**

# Regional Work for Global Results

Engineering, Operations & Technology | **Phantom Works**



Low-congestion  
TAs introduced  
at SFO

Miami TA  
Developmental  
Demonstration

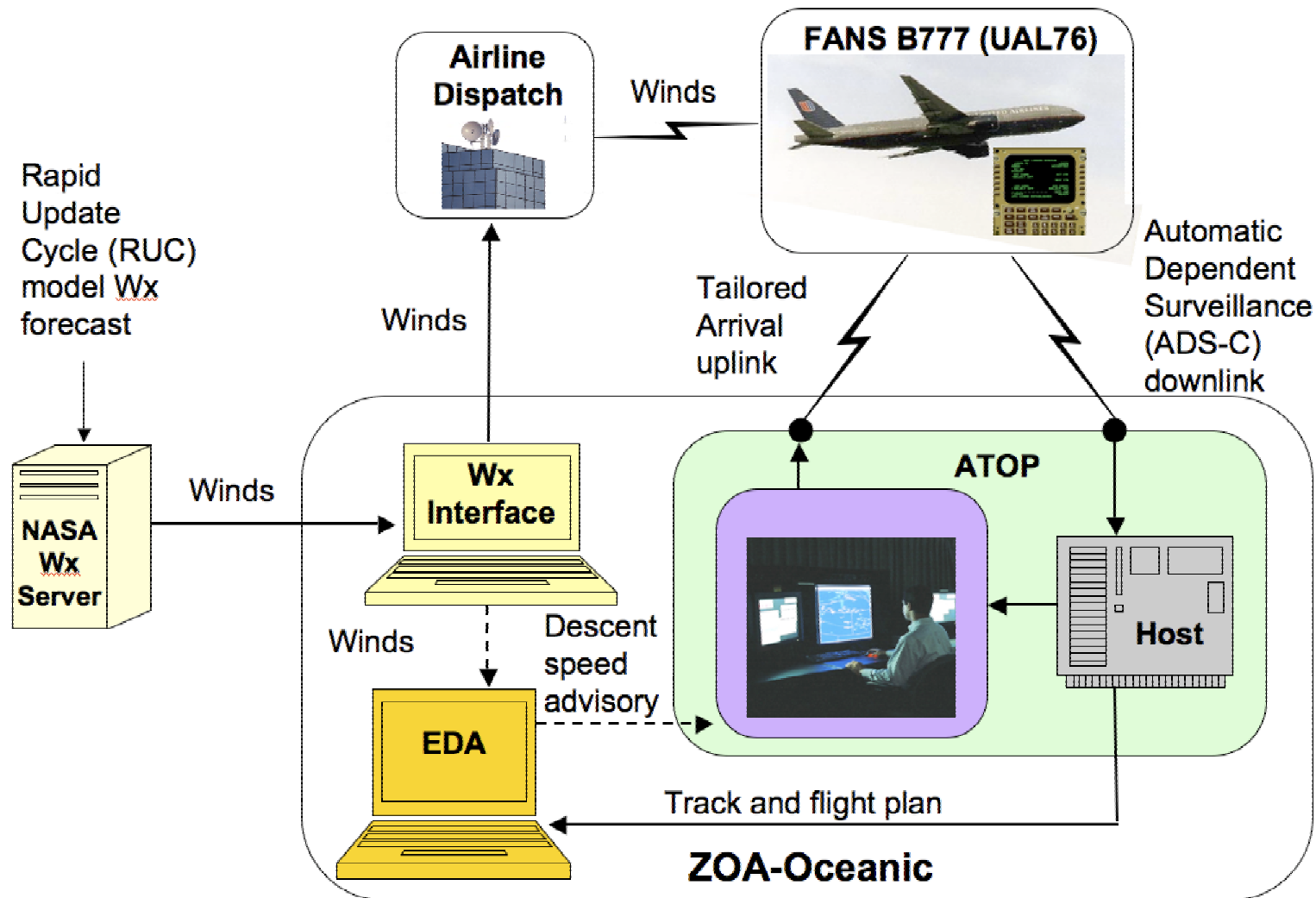
Amsterdam  
SARA Completion

High-congestion  
TAs Operational  
at Amsterdam

# OTA Field Trials at SFO

# OTA Field Trials: Systems Involved

Engineering, Operations & Technology | Phantom Works

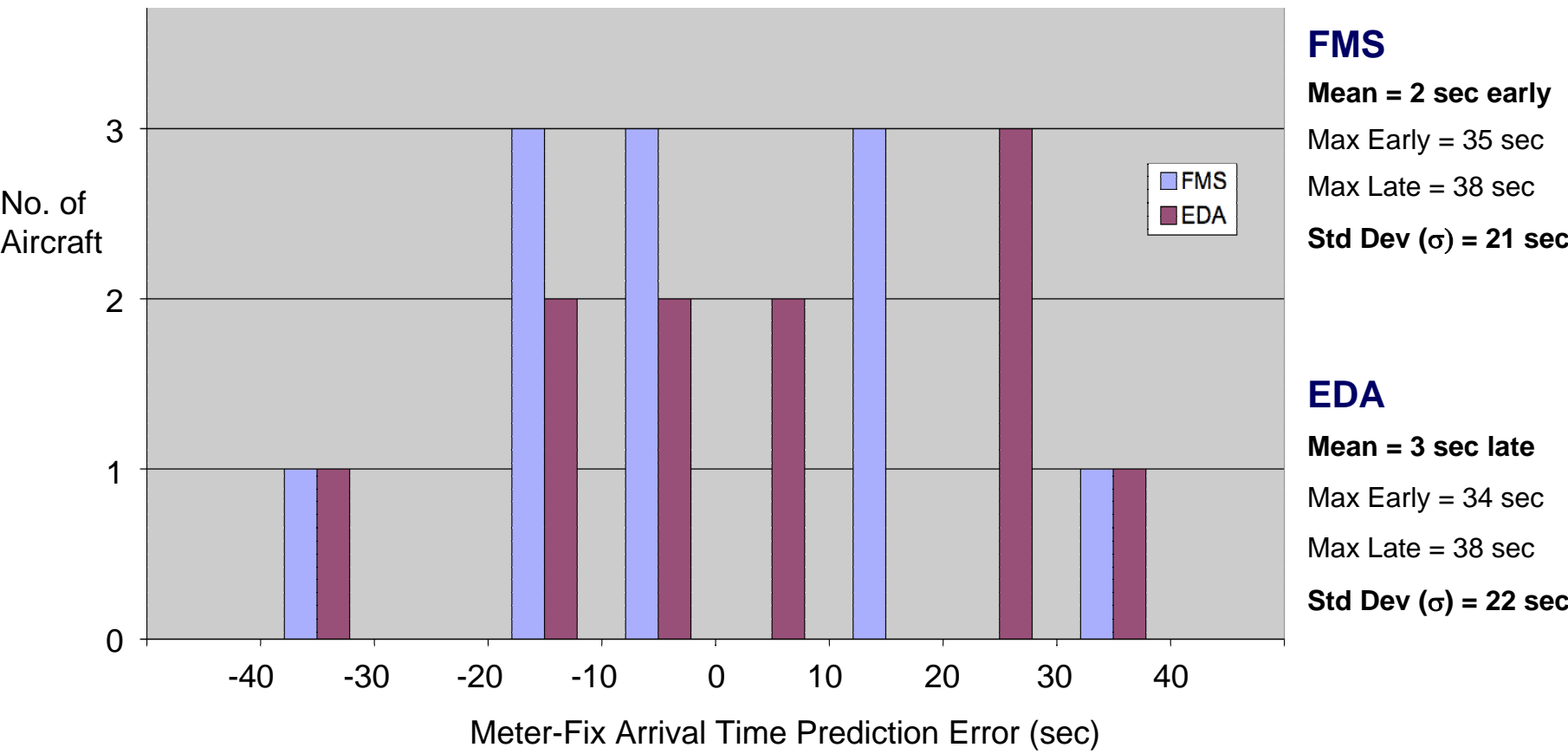




# OTA Results: FMS/EDA Arrival Time Prediction Error

Engineering, Operations & Technology | Phantom Works

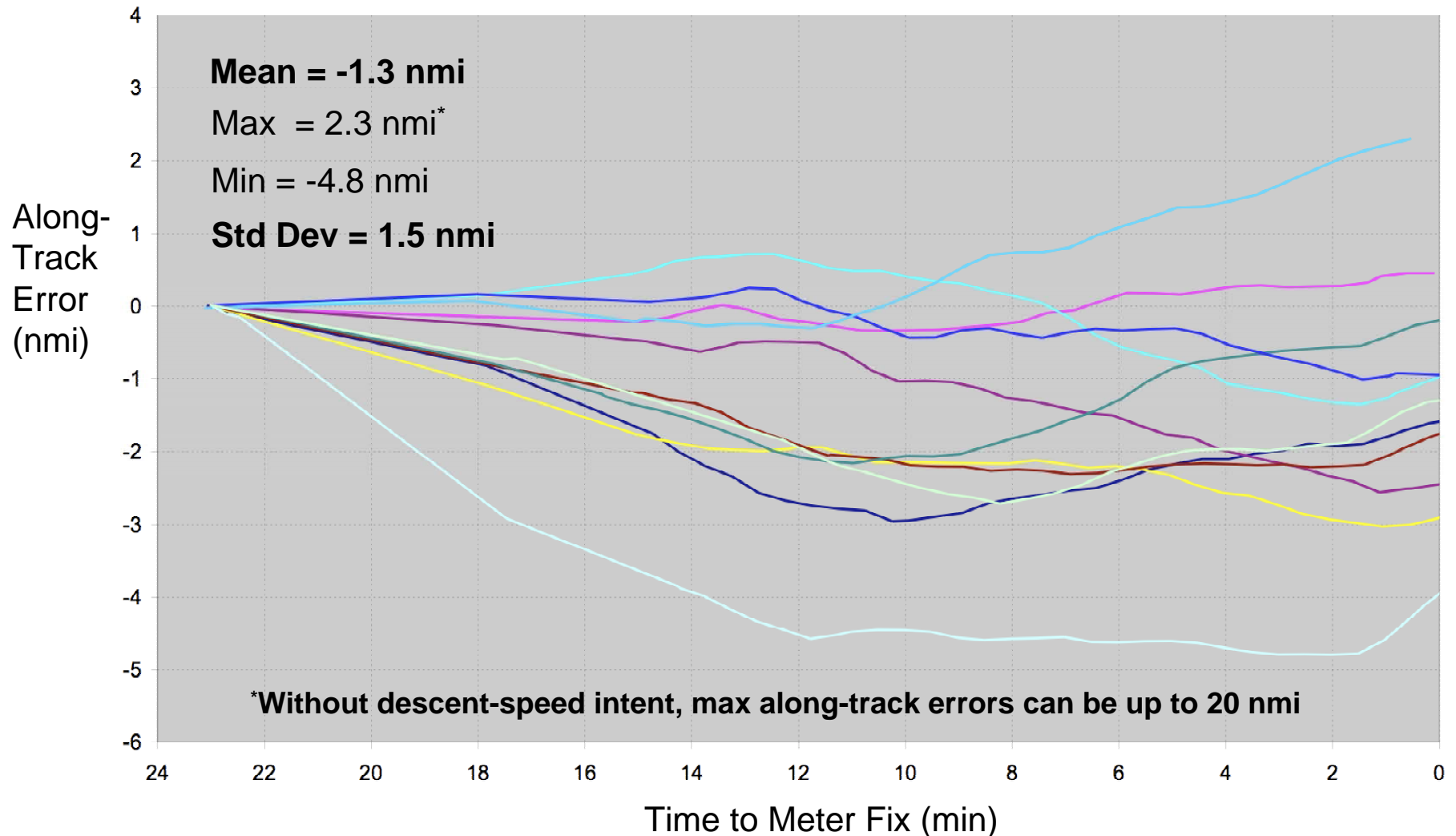
From single prediction, generated 200 nmi upstream of meter fix



# OTA Results: EDA Along-Track Prediction Accuracy

Engineering, Operations & Technology | Phantom Works

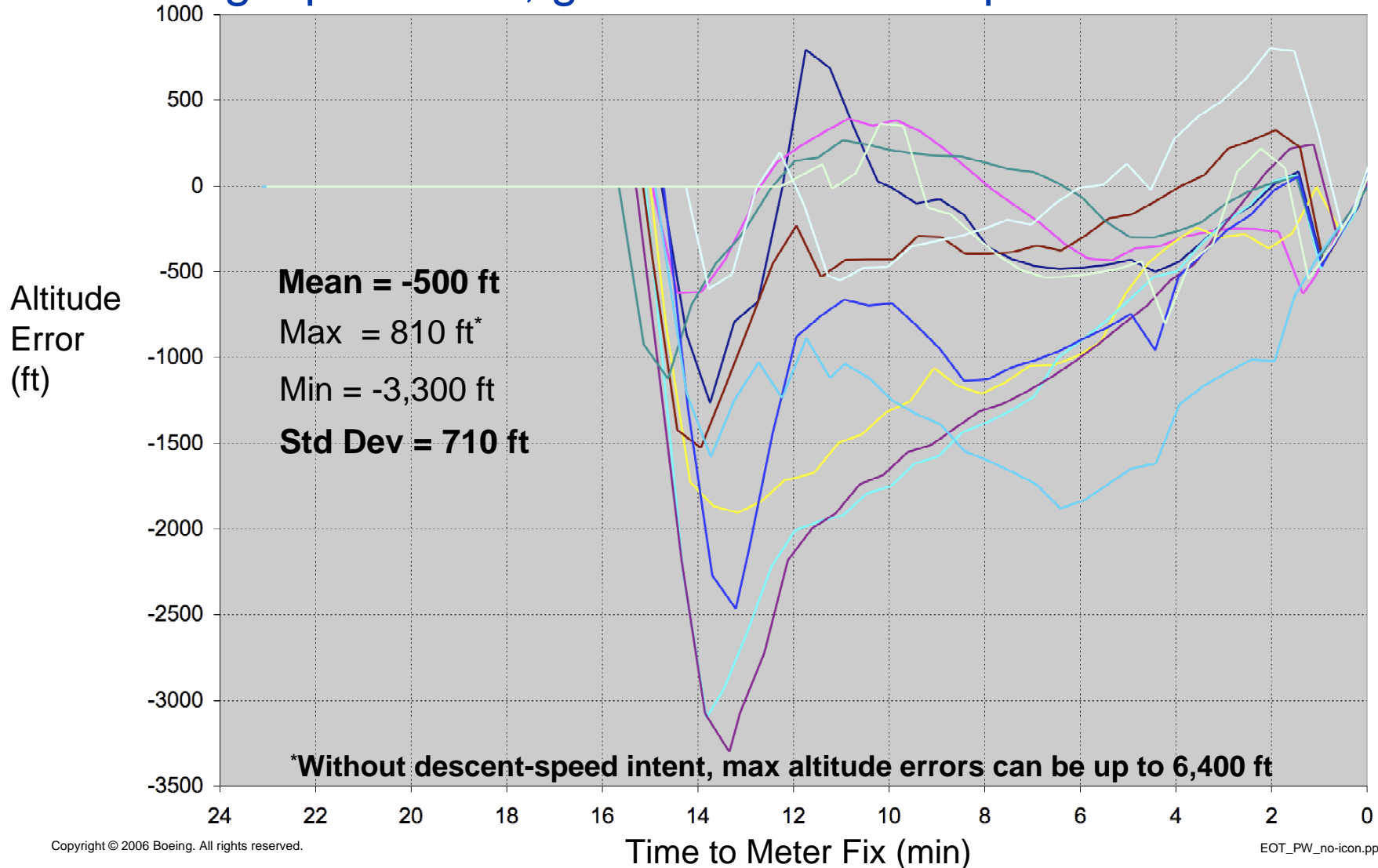
From single prediction, generated 23 min upstream of meter fix



# OTA Results: EDA Altitude Prediction Accuracy

Engineering, Operations & Technology | Phantom Works

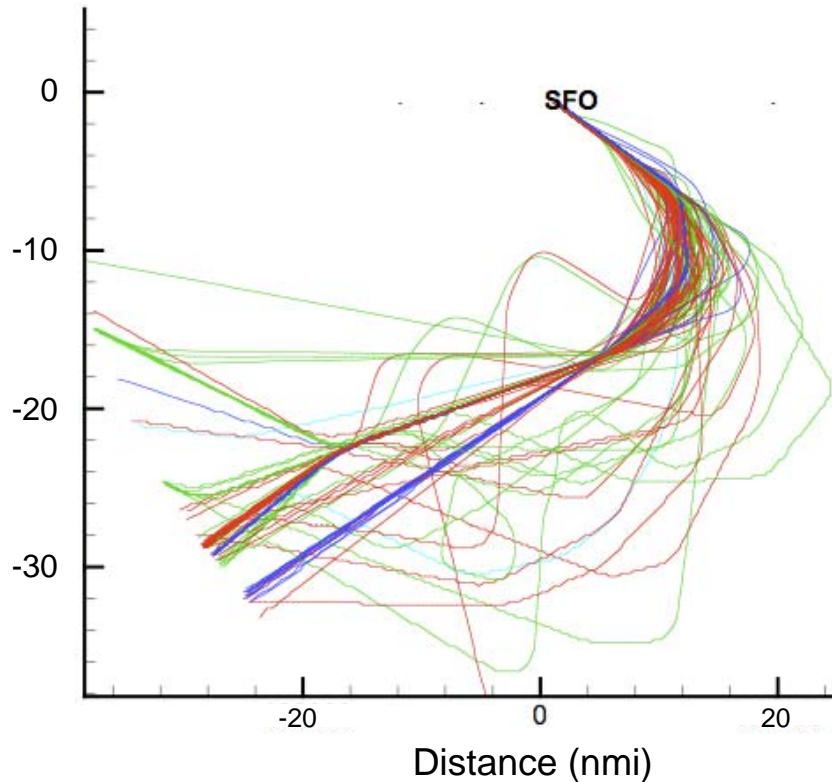
From single prediction, generated 23 min upstream of meter fix



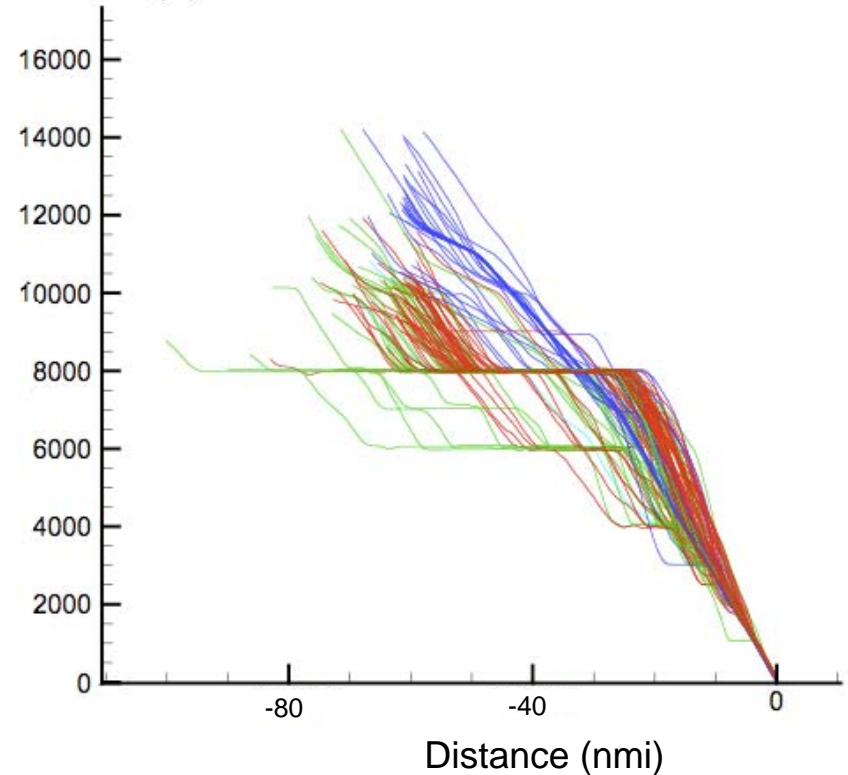
# OTA Results: Fuel/Emissions Benefit Baselines

Engineering, Operations & Technology | Phantom Works

Distance (nmi)



Altitude (ft)



Early Morning (includes OTA flights): 4 - 5 AM

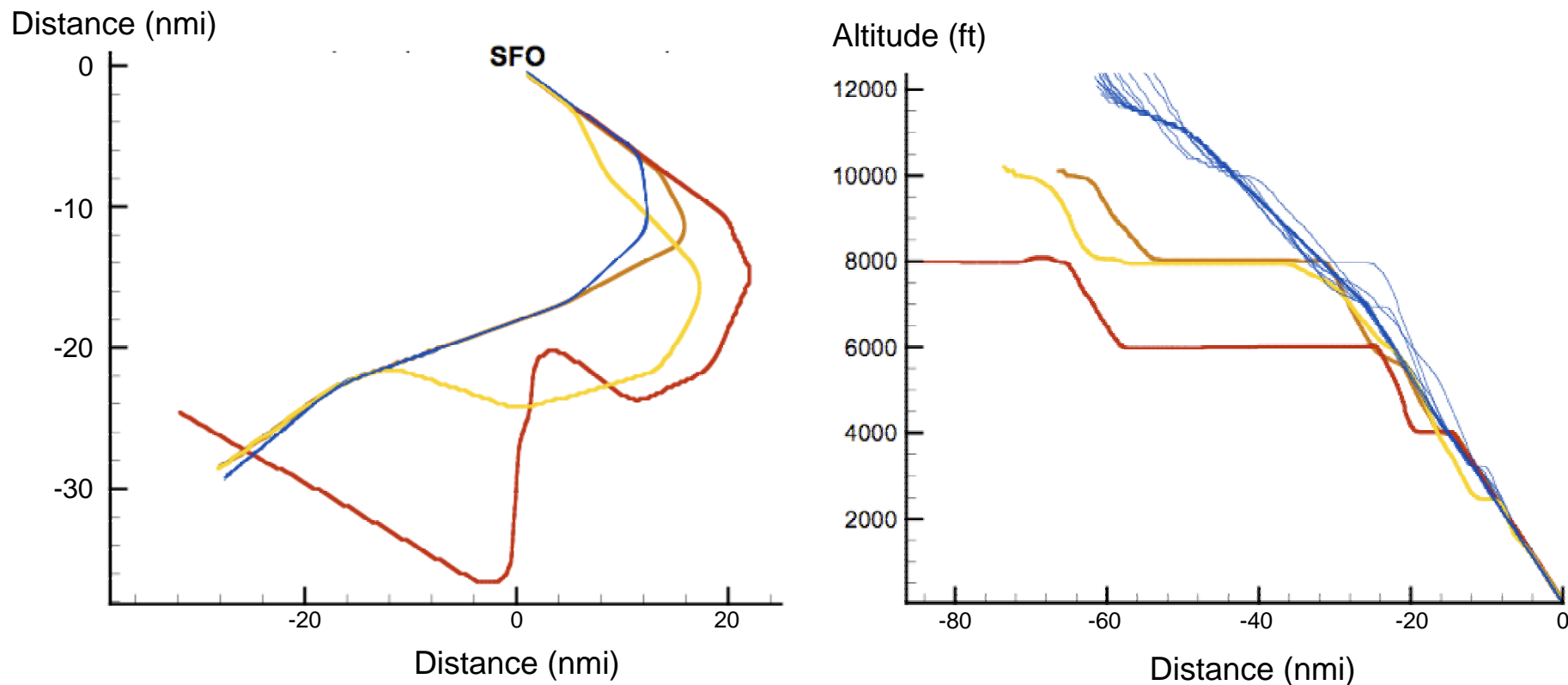
Morning: 7 - 11 AM

Early Evening: 5 - 6 PM

Evening: 7 - 10 PM

# OTA Results: Fuel/Emissions Benefit Baselines

Engineering, Operations & Technology | Phantom Works



- Tailored Arrival Flights
- Light Congestion Baseline
- Medium Congestion Baseline
- Heavy Congestion Baseline

# OTA Results: Fuel Benefits

Engineering, Operations & Technology | Phantom Works

		Distance flown from CREAN to SFO (nmi)	Fuel Burn from CREAN to SFO (lbs)	Fuel Savings (lbs)
Tailored Arrivals		233	7,500	
Baseline	Light	239	7,727	227
	Med	244	7,858	358
	Heavy	273	11,680	3,219

# OTA Results: Emissions Benefits

Engineering, Operations & Technology | Phantom Works

		Emissions from CREAN to SFO				
		CO (lbs)	NO <sub>x</sub> (lbs)	C <sub>x</sub> H <sub>x</sub> (lbs)	CO <sub>2</sub> (lbs)	CO <sub>2</sub> Savings (lbs)
Tailored Arrivals		17.5	134.0	0.77	23,618	
Baseline	Light	19.1	135.6	0.82	24,333	715
	Med	19.3	138.1	0.84	24,746	1,128
	Heavy	19.7	238.6	0.95	36,782	10,137

# EDA

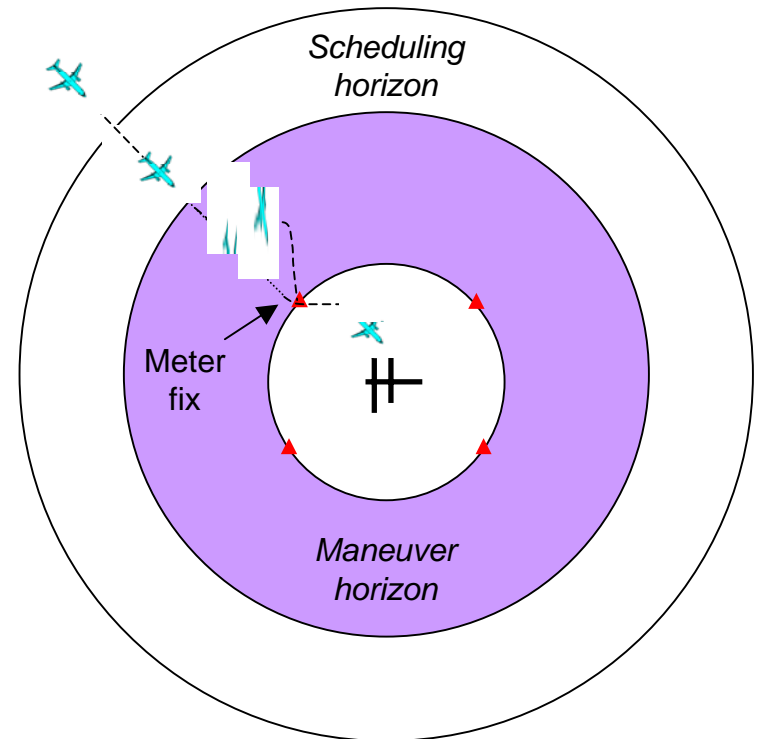
## *Status & Plans*



# EDA: Capabilities and Technical Challenges

Engineering, Operations & Technology | Phantom Works

- Provides speed/altitude/route advisories for tailoring CDA arrival solutions under capacity-constrained conditions
- Provides RTA-conformant CDA solutions that are also conflict free over entire trajectory
- Trajectory prediction accuracy and compatibility with airborne automation is primary challenge. Sensitive to:
  - Winds
  - Speed and route intent
  - Weight
  - Airplane aerodynamic and engine performance parameters



# EDA: Status

Engineering, Operations & Technology | Phantom Works

- **Currently under development in CTAS research software baseline**
- **Developed as an R-side tool for ARTCC sector controller**
  - **Controller-in-the loop simulations: 2001-2004**
  - **Adapted to support OTA field test: 2005-2007**
- **RTA algorithms mature, use combinations of cruise speed, descent speed, and path stretching**
- **Time-constrained, conflict resolution algorithms partially developed (work in progress)**
- **Improved matching of underlying trajectory synthesis algorithms with FMS currently being pursued, as a result of OTA findings**
- **Need to extend EDA into terminal area currently being assessed under NASA/Boeing Congested Airspace Tailored Arrivals (CATA) work**

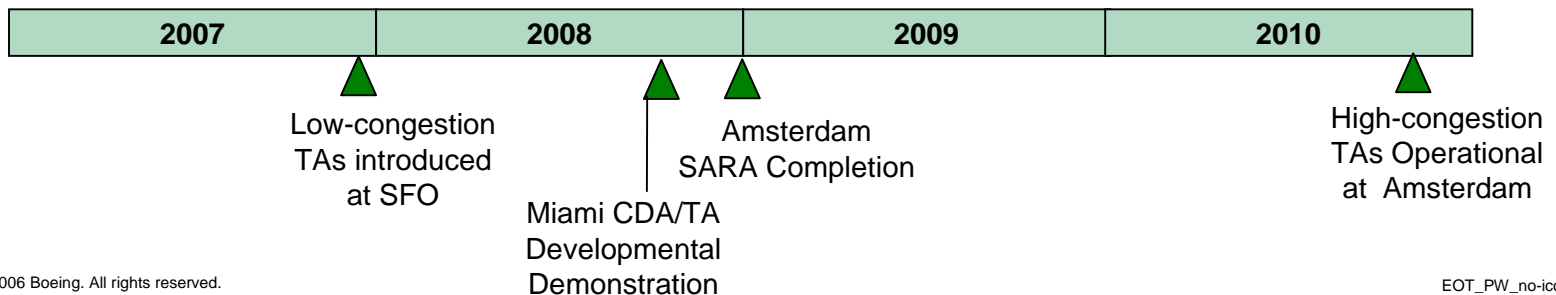
## Two-pronged Approach

- **NASA will continue to develop and refine:**
  - **Underlying algorithms associated with**
    - Trajectory synthesis
    - Conflict resolution
    - Supporting TMA scheduler
  - **Concepts and feasibility assessments associated with CATA**
- **FAA, Boeing and industry partners will lead nearer-term field applications with NASA support:**
  - **3D-Path Arrival Management (3D-PAM) at Denver**
  - **Atlantic Interoperability Initiative to Reduce Emissions (AIRE) at Miami**

# **Next Steps with U.S. Tailored Arrivals**

# Low-Medium Congestion Deployment Potential

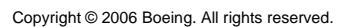
Engineering, Operations & Technology | Phantom Works



# **OTA Operational Deployment at SFO**

## ***Routes & Procedures***

## Engineering, Operations &amp; Technology | Phantom Works



Engineering, Operations &amp; Technology | Phantom Works



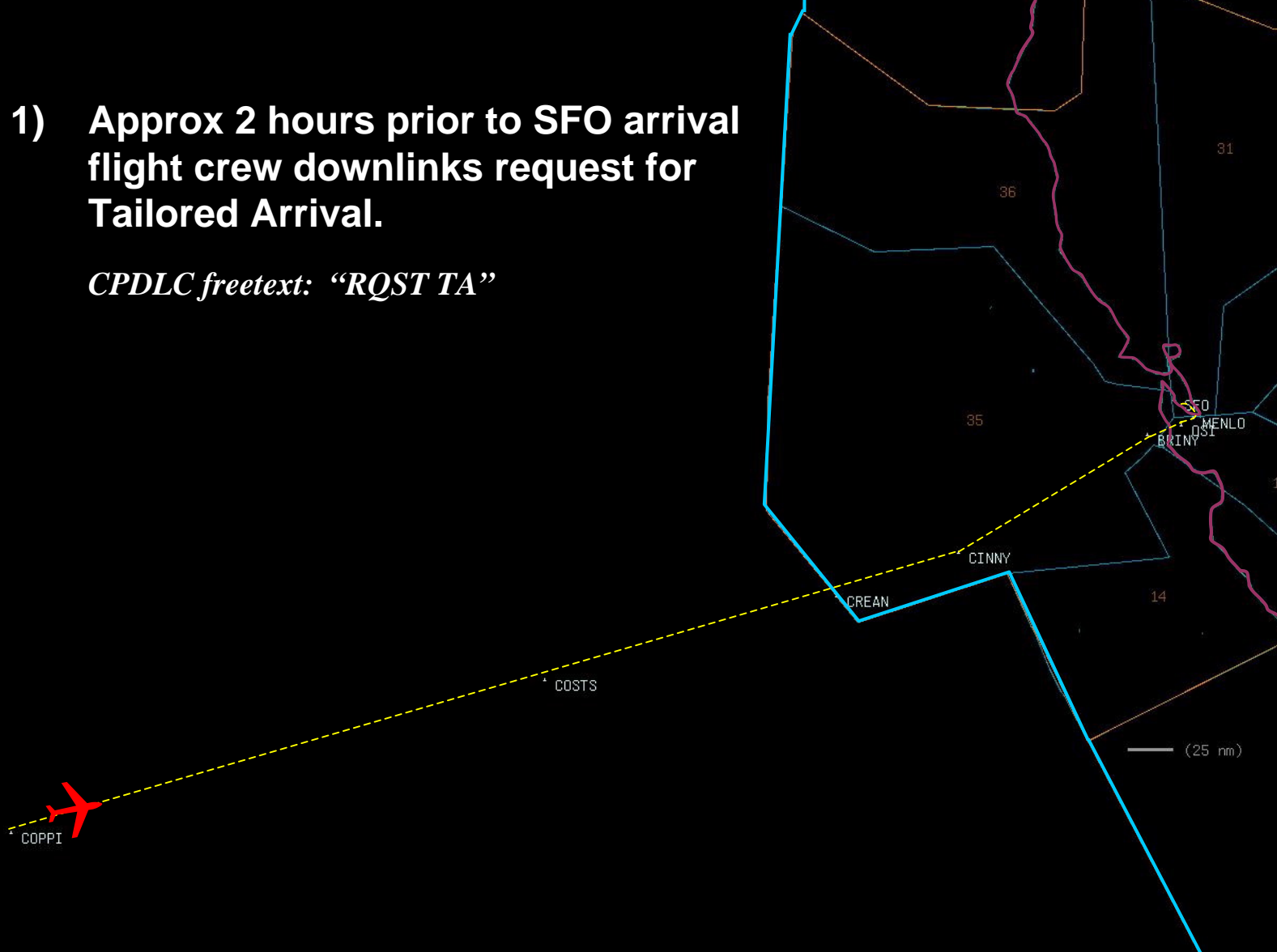
# Nightly procedures

Engineering, Operations & Technology | **Phantom Works**

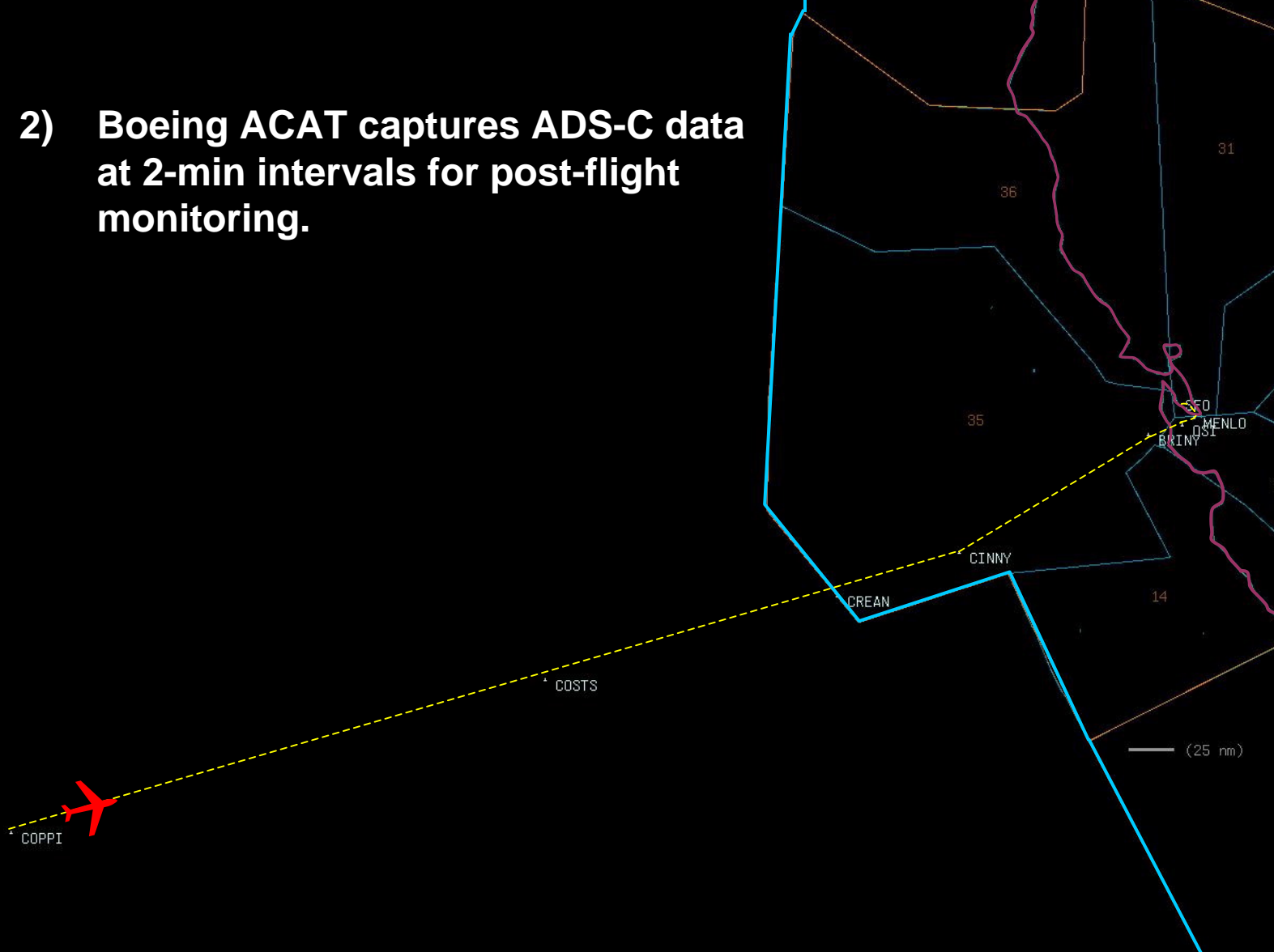
- ➔ List of approved airlines available to all airlines
  - ➔ Rich Shay will act as coordinator for all airlines to gain approval
- ➔ Approved playbook of Tailored Arrivals clearances available at all ATC Centers
- ➔ If a flight from an approved airline requests a TA via the following procedure, the controller will try to accommodate the request if the situation allows it
- ➔ All other standard operating procedures apply

1) **Approx 2 hours prior to SFO arrival  
flight crew downlinks request for  
Tailored Arrival.**

*CPDLC freetext: "RQST TA"*

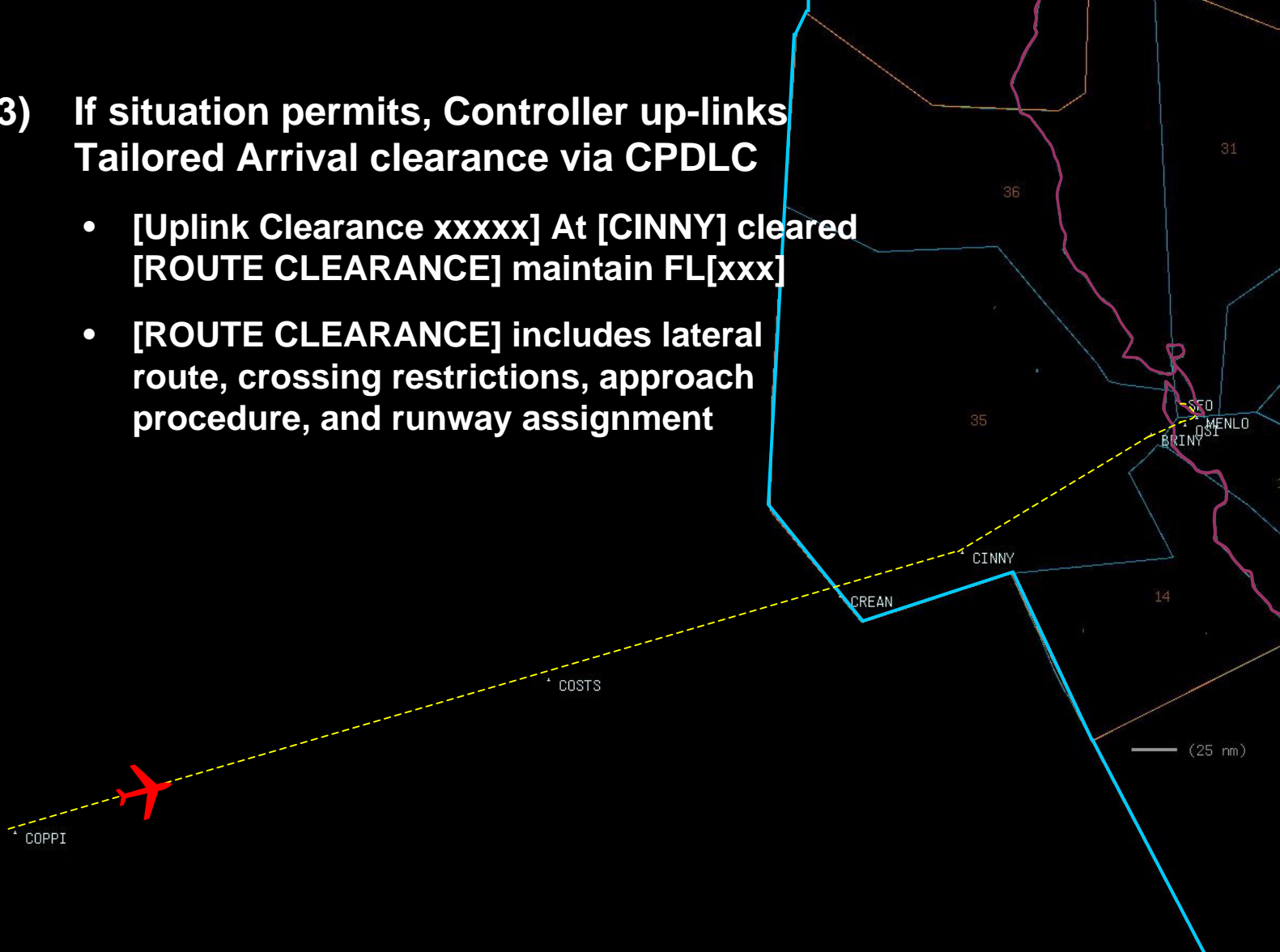


## 2) Boeing ACAT captures ADS-C data at 2-min intervals for post-flight monitoring.



### 3) If situation permits, Controller up-links Tailored Arrival clearance via CPDLC

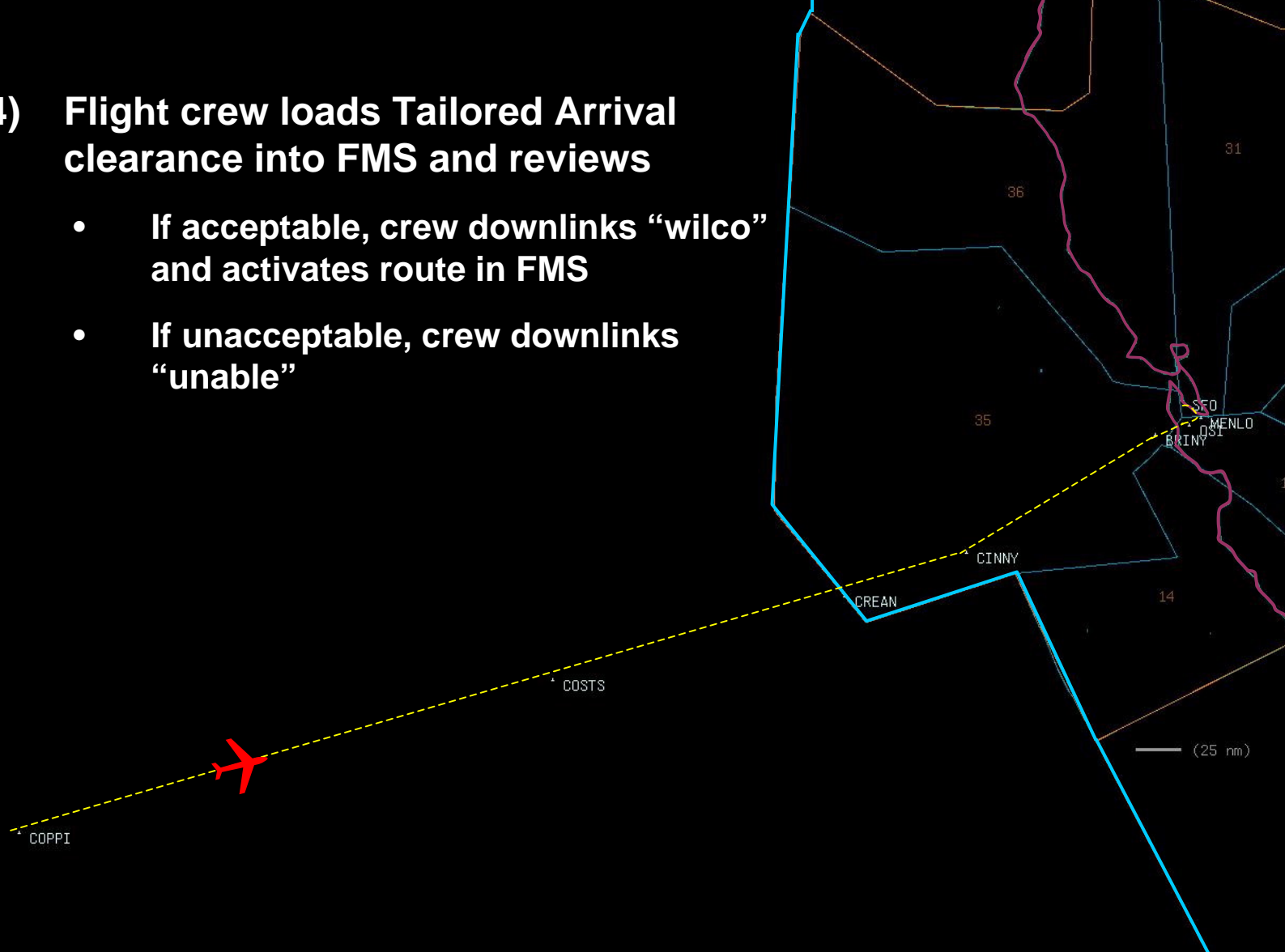
- [Uplink Clearance xxxxx] At [CINNY] cleared [ROUTE CLEARANCE] maintain FL[xxx]
- [ROUTE CLEARANCE] includes lateral route, crossing restrictions, approach procedure, and runway assignment



- “Uplink Clearance xxxxx” is an unambiguous and unique reference to this specific route and constraints, known by all ATC facilities involved

#### 4) Flight crew loads Tailored Arrival clearance into FMS and reviews

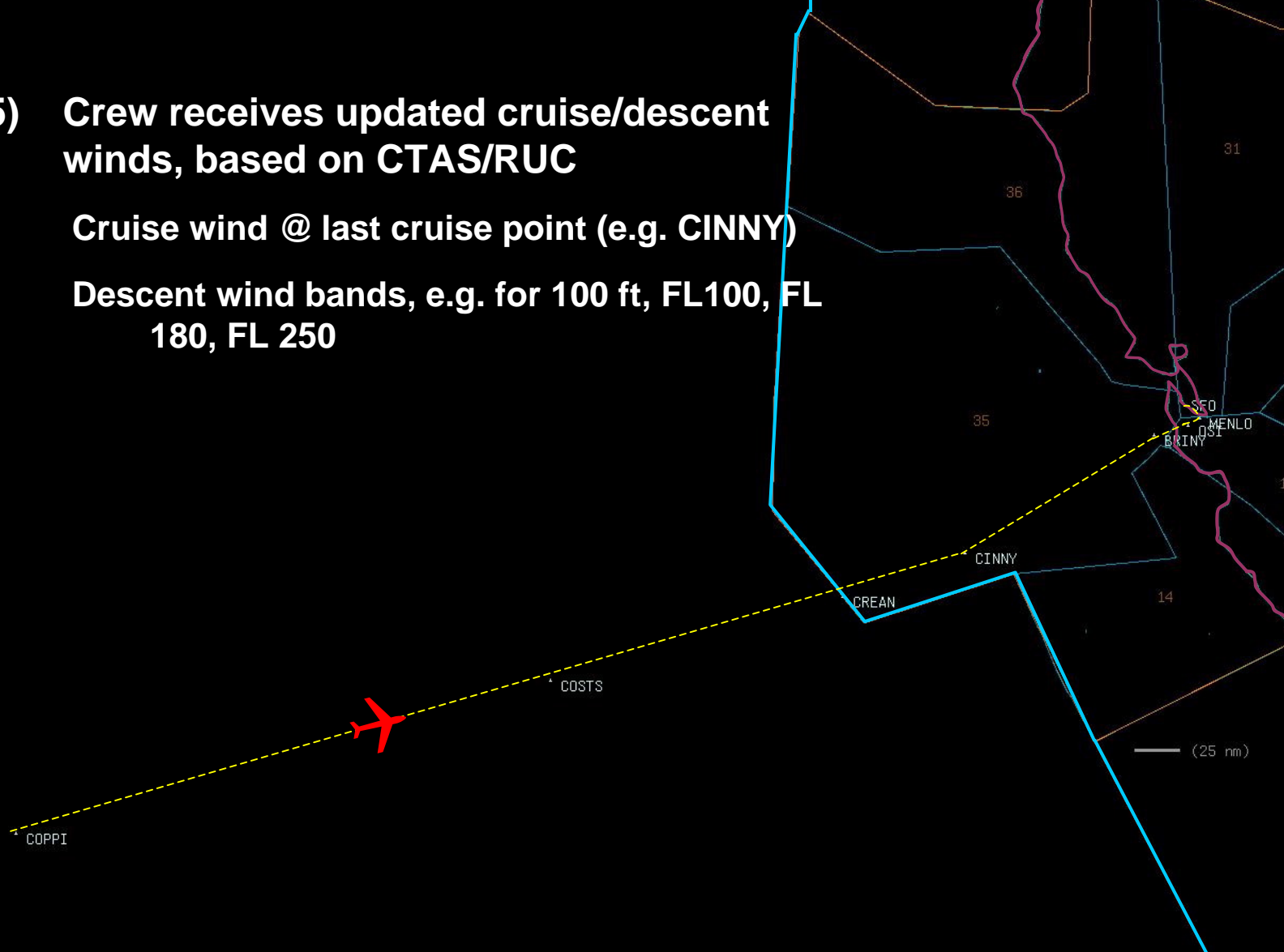
- If acceptable, crew downlinks “wilco” and activates route in FMS
- If unacceptable, crew downlinks “unable”



**5) Crew receives updated cruise/descent winds, based on CTAS/RUC**

**Cruise wind @ last cruise point (e.g. CINNY)**

**Descent wind bands, e.g. for 100 ft, FL100, FL 180, FL 250**



Not available for 3 Dec restart

## 6) Oceanic sector hands-off to ZOA sector controller

- CPDLC and ADS disconnected
- On contact with ZOA, aircrew checks in:  
“UAL 123 on the uplinked xxxxx route clearance”
- On radar contact ZOA controller advises:  
“UAL123 cleared via the uplinked xxxxx route clearance. Maintain FL[current flight level]”

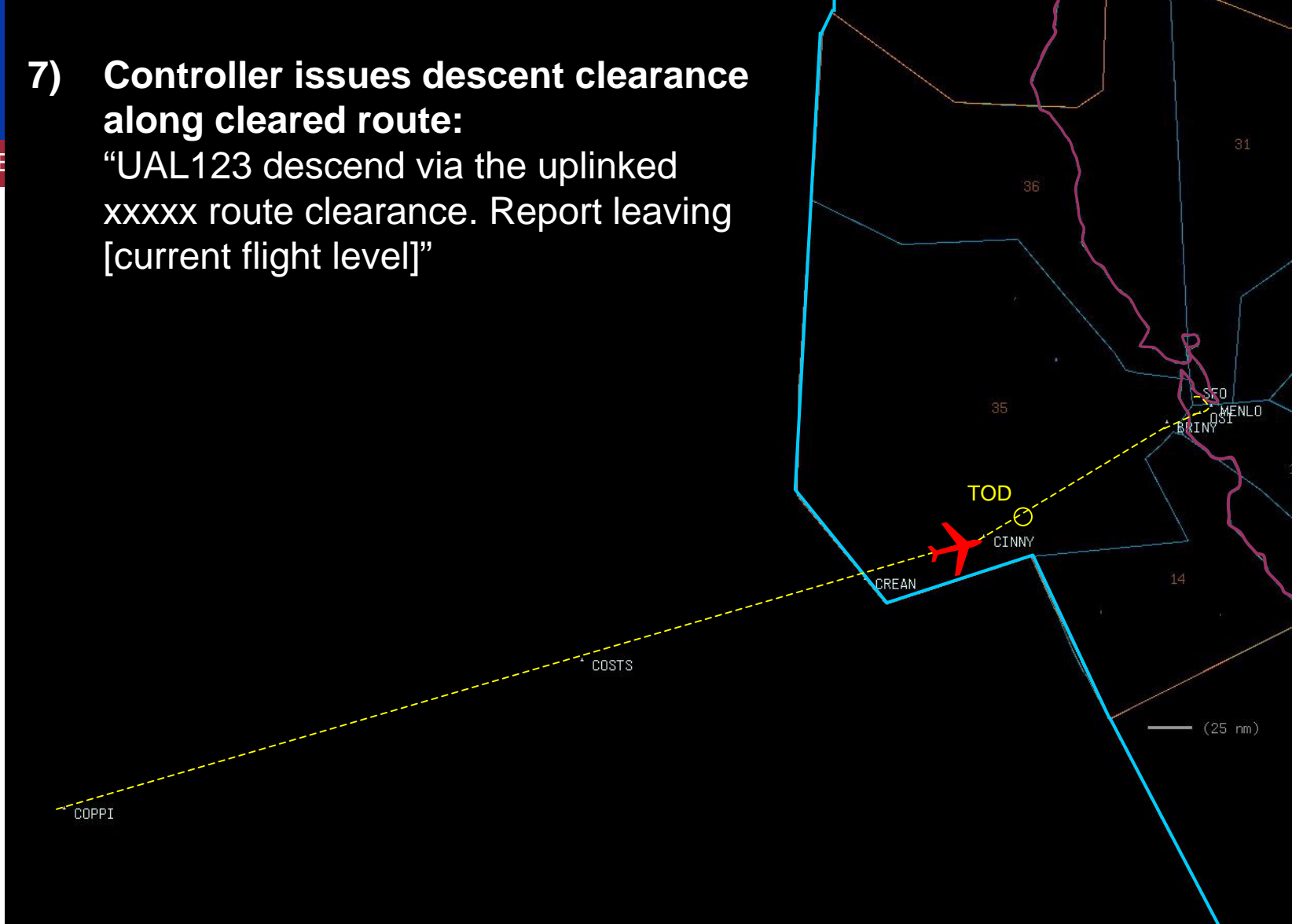


- Unambiguous confirmation of the cleared arrival route is communicated between ATC and the aircrew using the unique reference to this specific route and constraints, “Uplink clearance xxxxx”

- Radar controller has cleared route and assigned altitude on flight strip

7) **Controller issues descent clearance along cleared route:**

“UAL123 descend via the uplinked xxxxx route clearance. Report leaving [current flight level]”



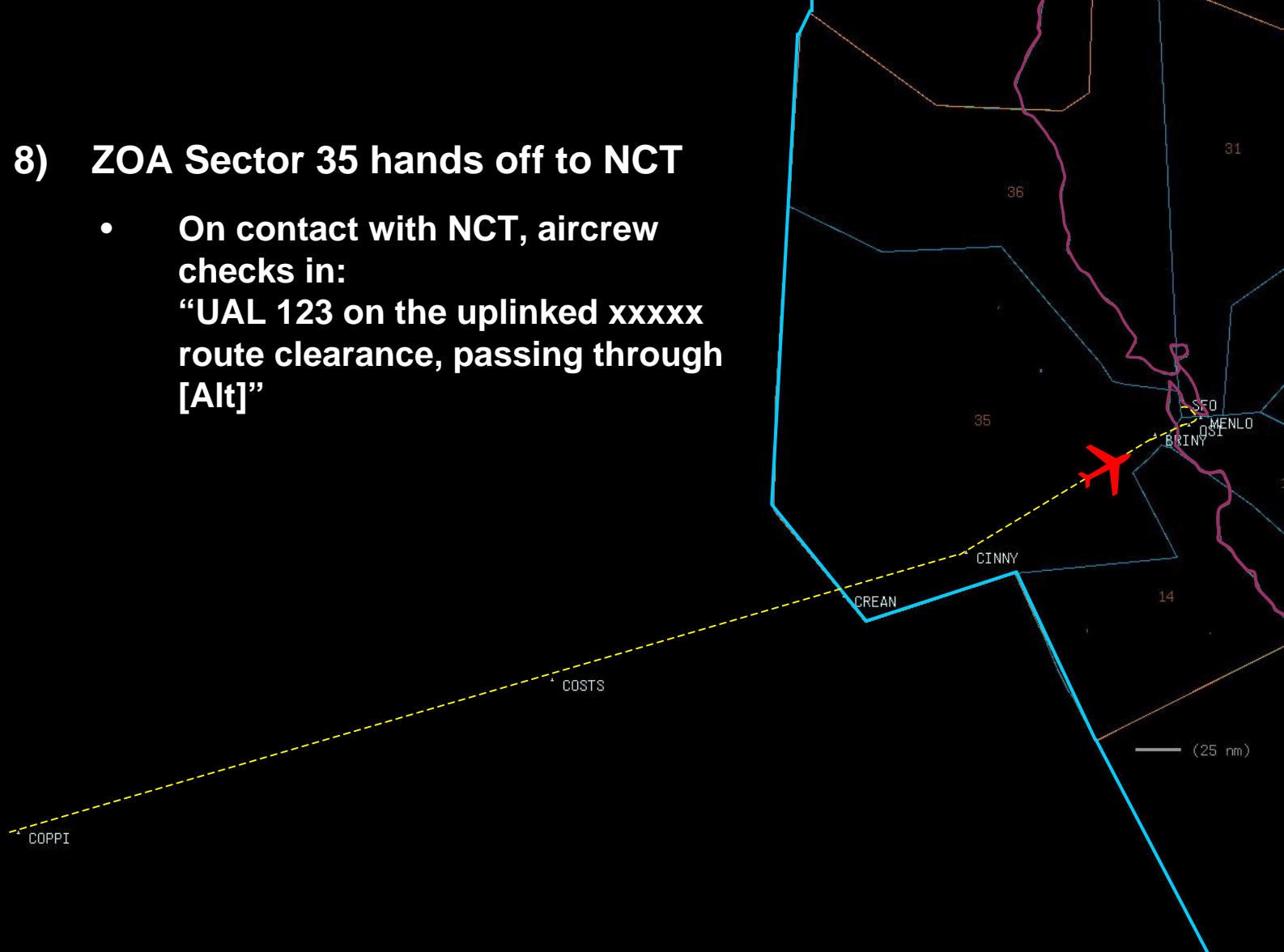
- Unambiguous confirmation of the cleared arrival route is communicated between ATC and the aircrew using the unique reference to this specific route and constraints, “Uplink clearance xxxxx”

- Radar controller has cleared route and assigned altitude on flight strip



## 8) ZOA Sector 35 hands off to NCT

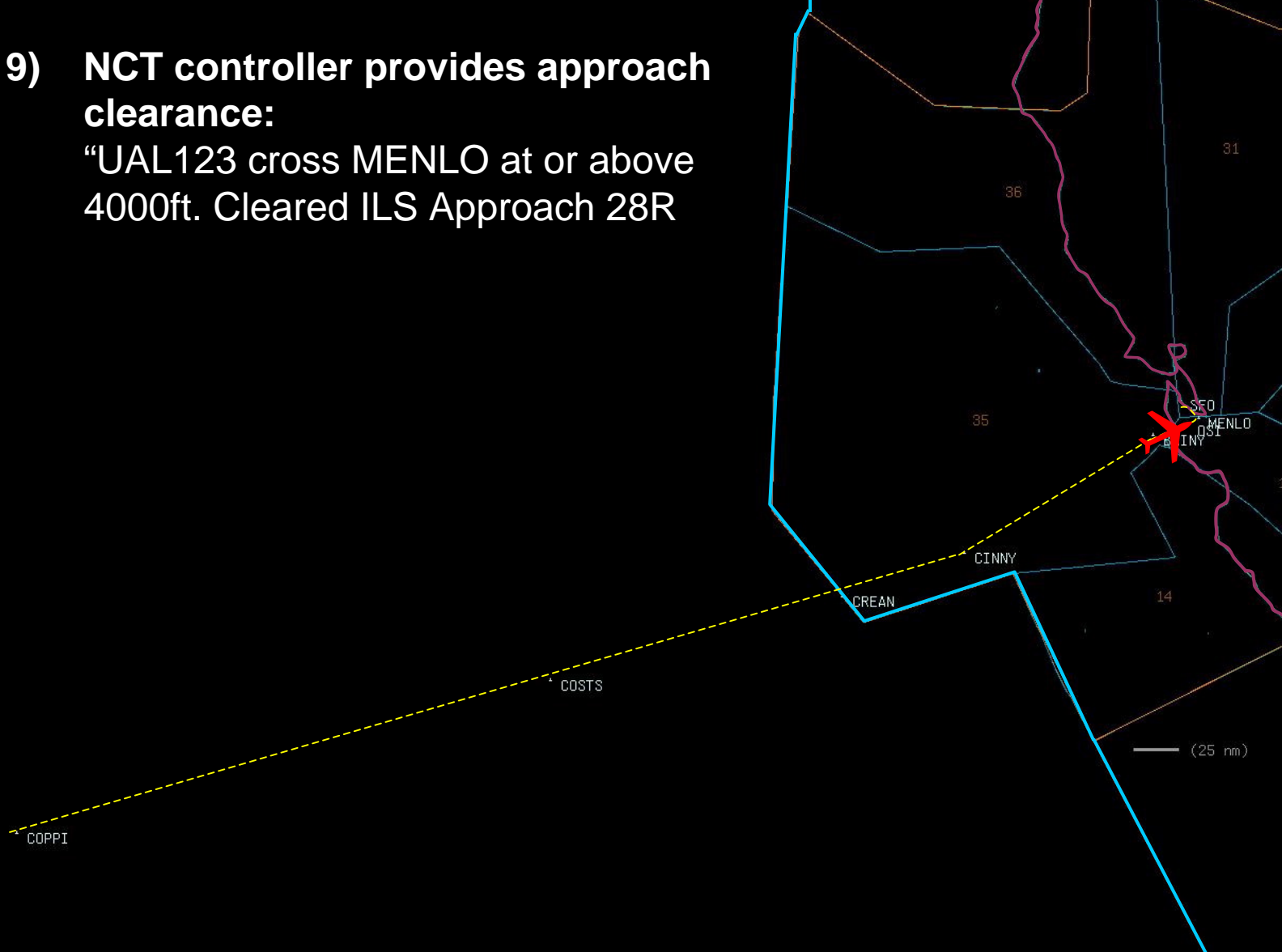
- On contact with NCT, aircrew checks in:  
“UAL 123 on the uplinked xxxxx route clearance, passing through [Alt]”



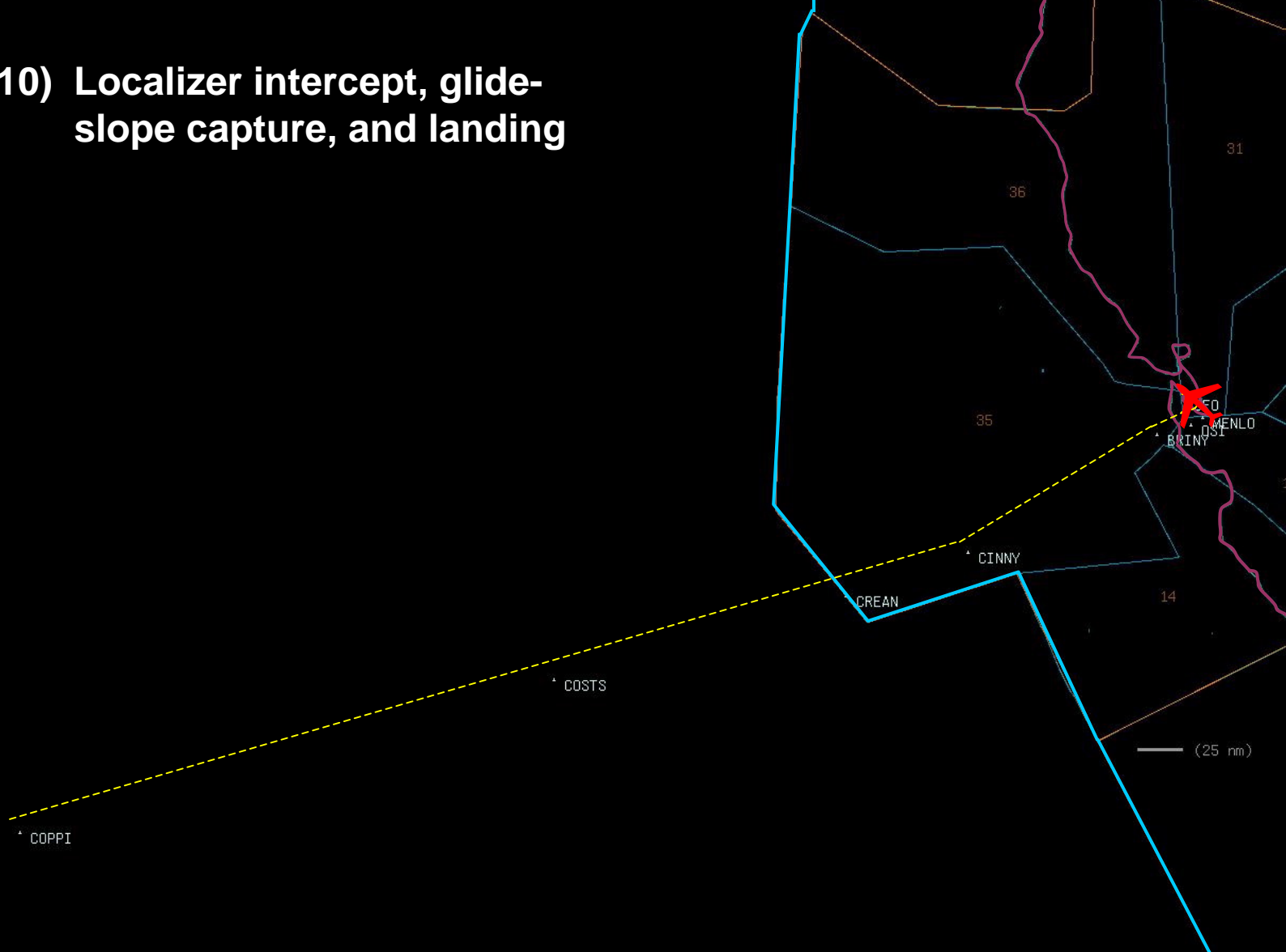
- Unambiguous confirmation of the cleared arrival route is communicated between ATC and the aircrew using the unique reference to this specific route and constraints, “Clearance xxxxx”

9) **NCT controller provides approach clearance:**

“UAL123 cross MENLO at or above 4000ft. Cleared ILS Approach 28R



## 10) Localizer intercept, glide-slope capture, and landing



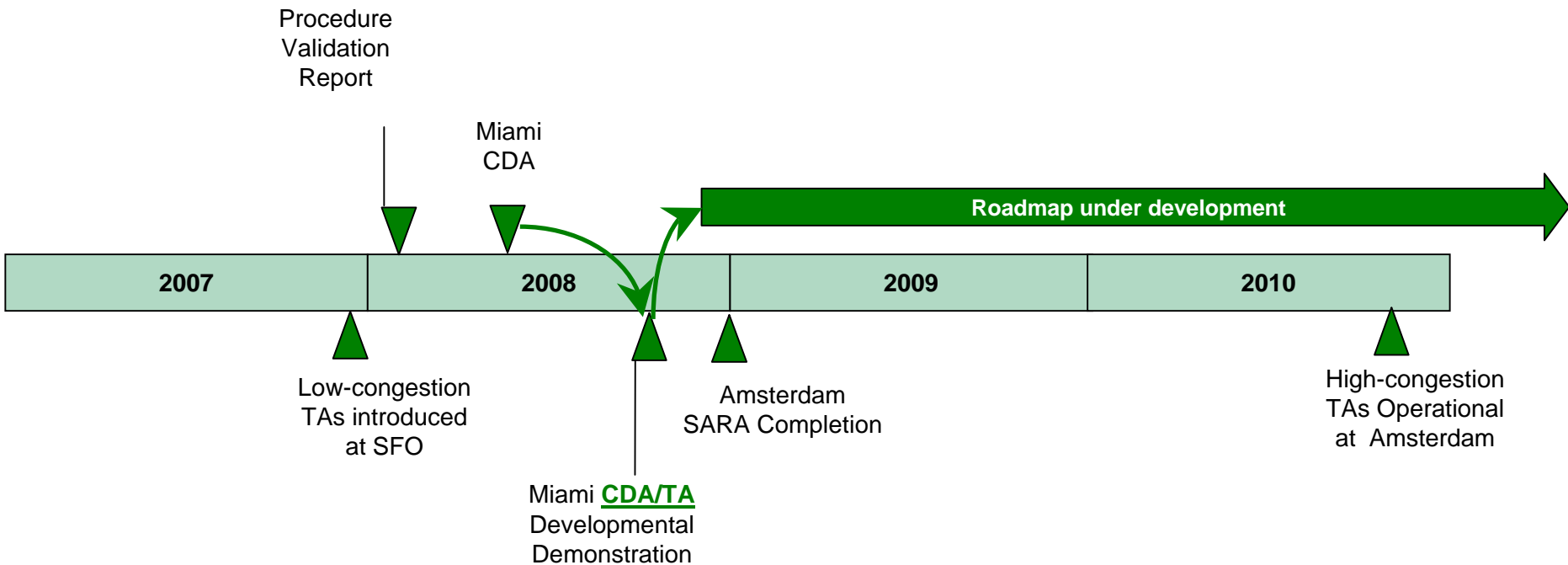
# Plan ahead

Engineering, Operations & Technology | **Phantom Works**

- **Boeing (Louis Bailey) to validate the PAINT and ALCOA transitions in support of PACOTS routes**
- **Airline additions**
  - QFA & ANZ probably first
  - JAL, ANA, NCA
- **Outstanding procedural items**
  - **Weather delivery method**
    - ATIS is not possible (yet)
    - We will start exploring two other options in Dec
  - **Obtaining descent speed sched to allow post flight EDA analysis**
    - UAL will add freetext downlink for trials period, probably within the TA request downlink
    - Will introduce this in Feb/Mar timeframe, after primary validation
- **Oceanic exit spacing**
  - Will work on mechanism for providing 12nm separation of two TA flights, at oceanic boundary, to improve chances for controllers to allow descent without intervention (initial options list: cruise-level RTA, speed, and cross-position-at-time).

# Broad Timeline

Engineering, Operations & Technology | Phantom Works



# Conclusion

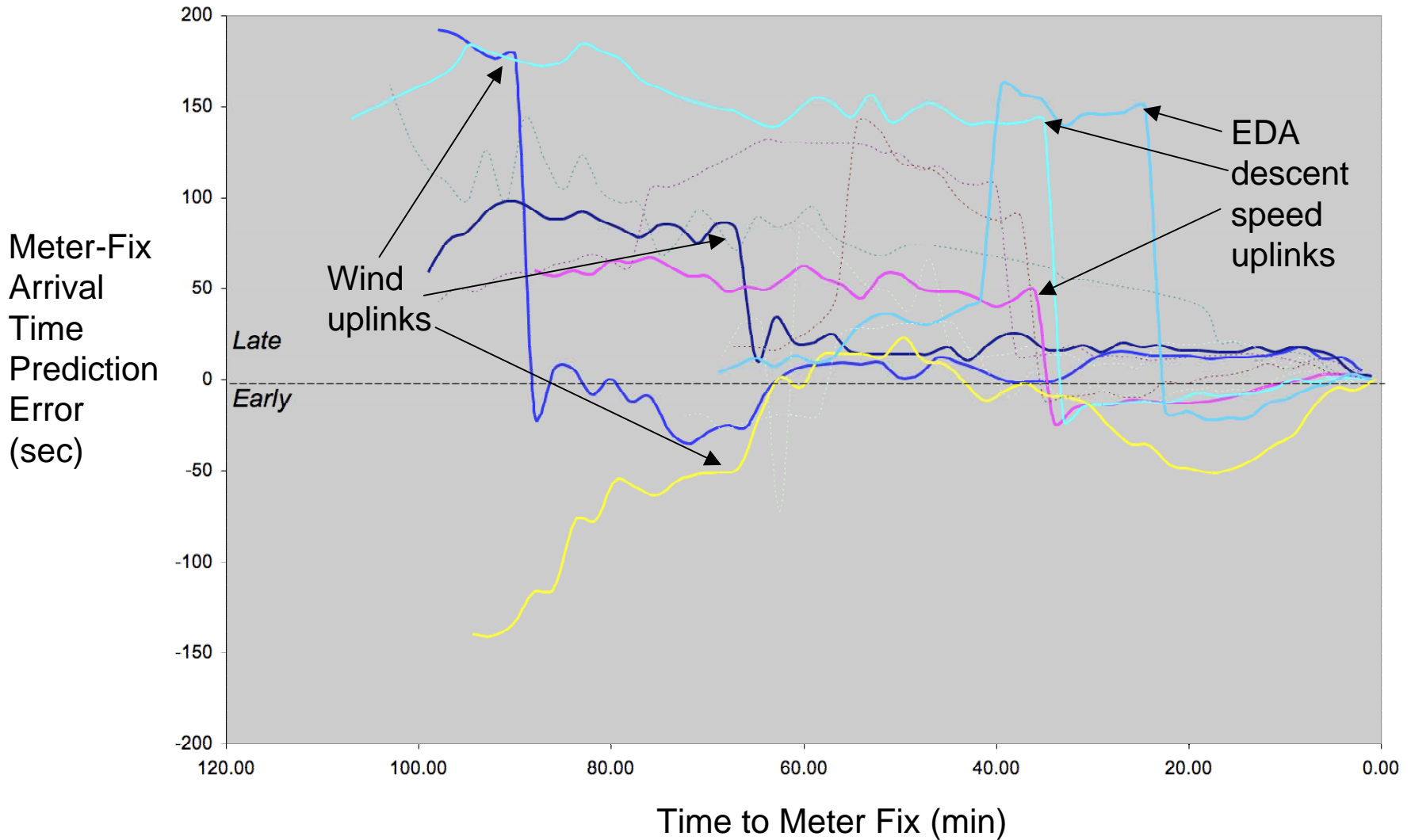
Engineering, Operations & Technology | Phantom Works

- **Tailored Arrivals are developing globally**
- **TA provides a good platform for exploration, validation and implementation of NextGen 4D trajectory-based operations**
- **SFO OTA trials instrumental in validating benefits, streamlining procedures, and identifying requirements for improving EDA**
- **Follow-on SFO OTA operational deployment commenced Dec 3, proceeding well**
- **Boeing is very supportive of the AIRE initiative to bring together multiple solutions for enabling efficient descents (i.e., CDA and TA)**
  
- **Thanks!**

# Related Topics and Backup

# OTA Results: FMS Arrival Time Predictions

Engineering, Operations & Technology | Phantom Works





# Integrated datalink

# Safer, faster ... CNS, not only 'C'

Engineering, Operations & Technology | Phantom Works

- Feedback to the flight crew to help counter, e.g.
  - Flight level busts
  - Incorrect frequency dial-in
  - Misinterpretation of clearances and exchanges
- Closed loop between the air and the ground
  - If ATS sends up a route change or constraint, it goes into the FMC as received from the ATS system
    - No re-key by the aircrew
    - What ATS sends is what the aircraft understands, or there is clarification by voice
    - Reduced ambiguity, improved safety, more predictability for air and ground
- And it allows new things ...



# Initial 4D Operations

**“UAL123 on the uplinked ALPHA route clearance”**

**”UAL123 cleared via the uplinked ALPHA route clearance”**

Engineering, Operations & Technology | Phantom Works

**ATC DL Uplink Message AT1 - ATCCTR1 - .N777BO - CRC is valid**

**19,,**

**0(169) : [UPLINK CLEARANCE ALPHA]**

**0(83) : At [pos] Cleared [routeclr]**

**pos(fix): COSTS**

**dest airport(): KSFO**

**arr runway(): 28R**

**app proc(): APP,ILS28R,MENLO**

**route info(): 5**

**(pub): CINNY**

**(pub): BRINY**

**(l/l): N37W122**

**(pub): OSI**

**(pub): MENLO**

**route info add():**

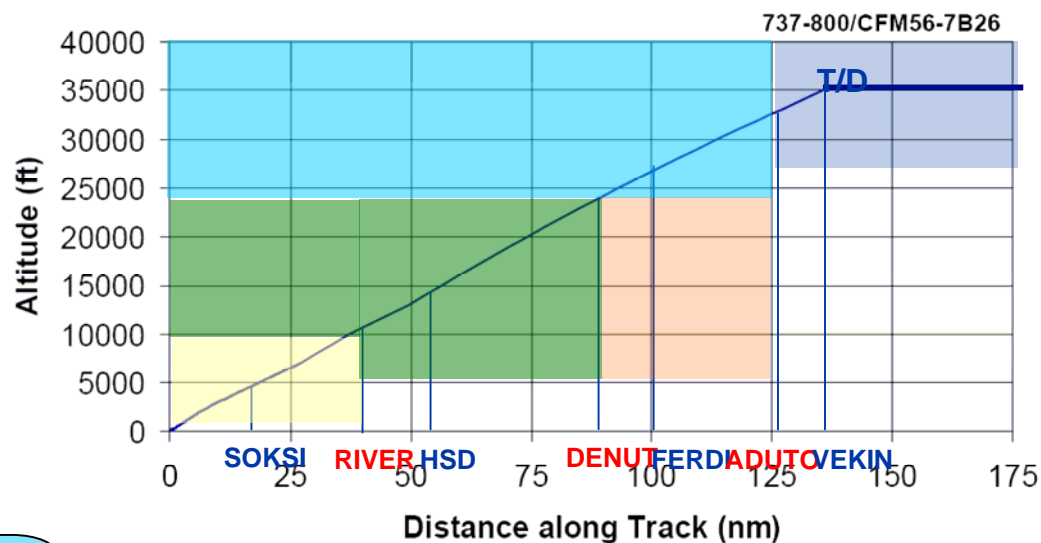
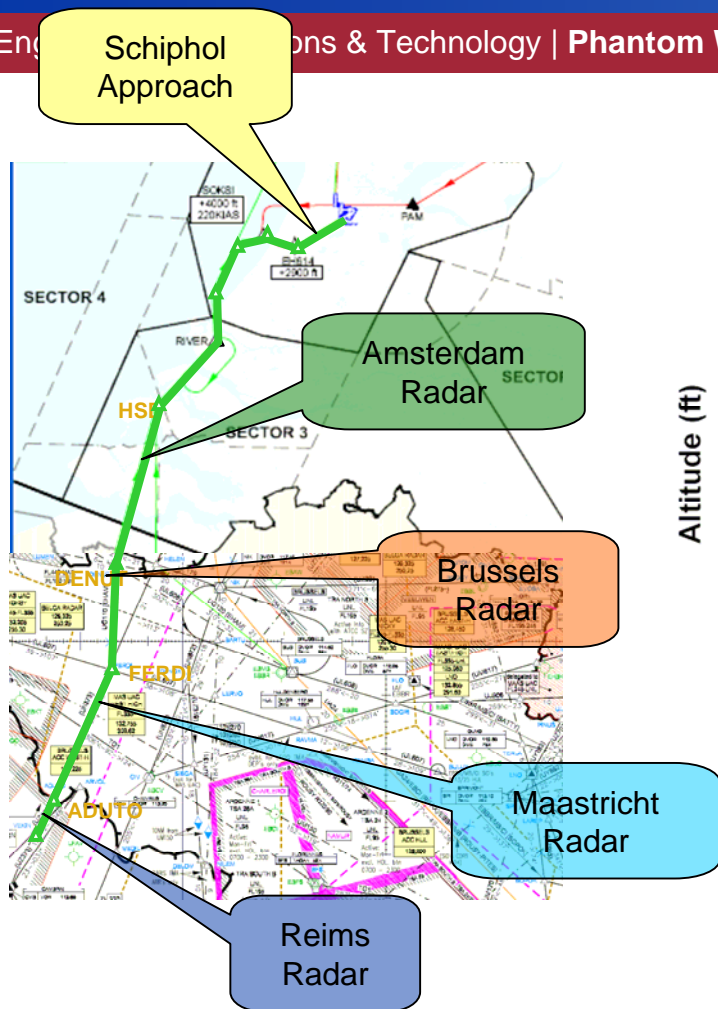
**wp spd alt: 2**

**pos(l/l): N37W122; spd(ias): 210; ATWalt(qnh): 7500A**

**pos(fix): MENLO; ATWalt(qnh): 4500A**

# And finally, returning to a key point in 4D

Engineering & Technology | Phantom Works



- How do I make sure that all these entities have the same picture?
- There is certainly a great way to do that in the new systems coming in e.g. 2025
- But what about today and the transition to 2025?

# Tailored Arrivals and datalink

Engineering, Operations & Technology | Phantom Works

- **We always design to datalink in Tailored Arrivals**
  - Even when we are using a voice solution due to ...
- **The functions used**
  - Are available on all current production Boeing and Airbus aircraft
  - Rely on an already certified and approved datalink system
  - Are essentially the same for ATN and FANS, provided the implementation is integrated
- This is an initial 4D operation
- There are some known shortcomings, e.g.
  - RTA or “cross at” times are not fine enough for the a/c
  - Downlinked intent data could be improved significantly
  - So far, no showstoppers
  - These are not necessarily unique to FANS-1/A
  - We are cataloging and working on these with industry via ICAO, SC214, ....

# **Downlink Trajectory Data**

## **(ATS certified and approved systems)**

# FANS-1/A ADS-C Intermediate Projected Intent

Engineering, Operations & Technology | Phantom Works

- **ADS Downlink Message ADS - ATCCTR1 - .N777BB - CRC is valid**
- **Basic,N35-44.0,W126-5.5,37000,53: 3.0,NO TCAS,2,REDUNDANT**
- **InterIntent,0.125,Valid,-125.2,37000,00:03:48**
- **InterIntent,108.875,Valid,59.3,37000,00:17:04 <---Top of Descent**
- **InterIntent,81.875,Valid,60.5,12000,00:29:28 <--- BRINY**
- **InterIntent,7.500,Valid,73.7,10000,00:31:00 <--- 10K decel**
- **InterIntent,11.375,Valid,73.8,7000,00:33:32 <---OSI**
- **FixedIntent,N37-35.6,W122-17.6,1188,00:35:28 <---DARNE (end of descent point)**



# ATN ADS-C Intent

Engineering, Operations & Technology | Phantom Works

- **Provides several improvements, e.g.**
  - **More than two points with ETAs**
  - **Intent points in lat/long rather than distance and track**
- **But most of the most important issues are the same**
  - **Lack of gross weight**
  - **Lack of speed schedule**
  - **Lack of “soft” points**
  - **Lessons learned from FANS such as offset definitions**
- **As no one was building an ATN ADS-C**
  - **With Airbus, approached ICAO to define Next Gen ATN ADS-C, covering these issues and other lessons learned**

# Vertical waypoint types

- Top of climb (*where climb stops and cruise FL is reached*)
- Top of descent (*where cruise FL is left and descent starts*)
- Start of step climb (*Where climb starts to reach a new cruise FL*)
- End of step climb (*where climb stops and new cruise FL is reached*)
- Start of step descent (*where descent starts to reach a new cruise FL*)
- End of step descent (*where descent stops & a new cruise FL is reached*)
- Start of cruise climb segment (*where a cruise climb segment starts*)
- End of cruise climb segment (*where a cruise climb segment ends*)
- Level off (*level step when in climb or descent*)
- Start of descent (*where descent is resumed after level off*)
- Start of climb (*where climb is resumed after level off*)
- CMS waypoint (*Constant Mach segment*)
- Cross over altitude (*where the limit between IAS and Mach is reached*)
- Transition altitude (*where the limit between QNH and FL is reached*)
- Speed change (*where a speed change of more than 10 knots IAS or 0.10 Mach is planned to be initiated*)



# Lateral waypoint types

- From (last sequence waypoint)
- To (next sequence waypoint)
- Offset start (where aircraft leaves the parent path)
- Offset reached (where aircraft reaches the parent path)
- Return to parent path initiation (where aircraft initiates its return to the parent path)
- Offset end (where aircraft reaches the parent path)
- Offset (waypoint which is an offset waypoint but which is neither the offset start/end waypoint nor the offset reach/return to parent path waypoints)
- Non flyable (sequence of waypoint where the FMS is not able to compute a flyable trajectory. It should not occur in nominal conditions where procedures to be flown are adapted to aircraft capabilities)
- Discontinuity (discontinuity in the FMS flight plan)
- Overfly (waypoint to be overflowed – this changes the way to build the trajectory in case of turn)
- Hold (waypoint where a hold is initiated and left)
- Procedure turn (U-turn = defines a course reversal starting at a specific database fix and including an outbound leg followed by a Left or Right turn and a 180° course reversal to intercept the reverse leg)

# “Integrated datalink”

Engineering, Operations & Technology | Phantom Works

- **Integrated datalink is essential to our ATM vision, enabling:**
  - Decrease in reaction time and reduction of frequency occupancy
  - Seamless interoperability and operations thru flight domains
  - 4-D Trajectory negotiation and separation
  - Large-scale data sharing of aircraft intent, ground & air
  - Airspace redesign
- **Integrated datalink includes a full CNS solution (CNS, not only 'C')**
  - **Datalink applications**
    - CPDLC: Controller Pilot Data Link Communications
    - ADS-C: Automatic Dependant Surveillance-Contract
    - Others, e.g: AOC, etc...
  - For aircraft, the capability to interface with avionics (HMI, RMP, FMC...)
  - For ANSPs, the capability to share and use ATM data
    - Primary examples: frequency change, flight plan consistency, flight plan conformance, route clearance, trajectory negotiation

# The result

- **The crew manages; the aircraft flies**
  - Individual crew tendencies reduced
  - Individual airline tendencies reduced
  - Aircraft more predictably do what ATS expects
  - More safeguards in place to reduce navigation errors
- **Faster responses**
  - Cockpit procedure to review, load, and coordinate uplink eased considerably
  - The biggest source of operational response time reduced
- **Etc...**
- **Pre-requisite for many new concepts, such as those centering on 4D Operations**

# Vertical deviation event contract

Engineering, Operations & Technology | Phantom Works

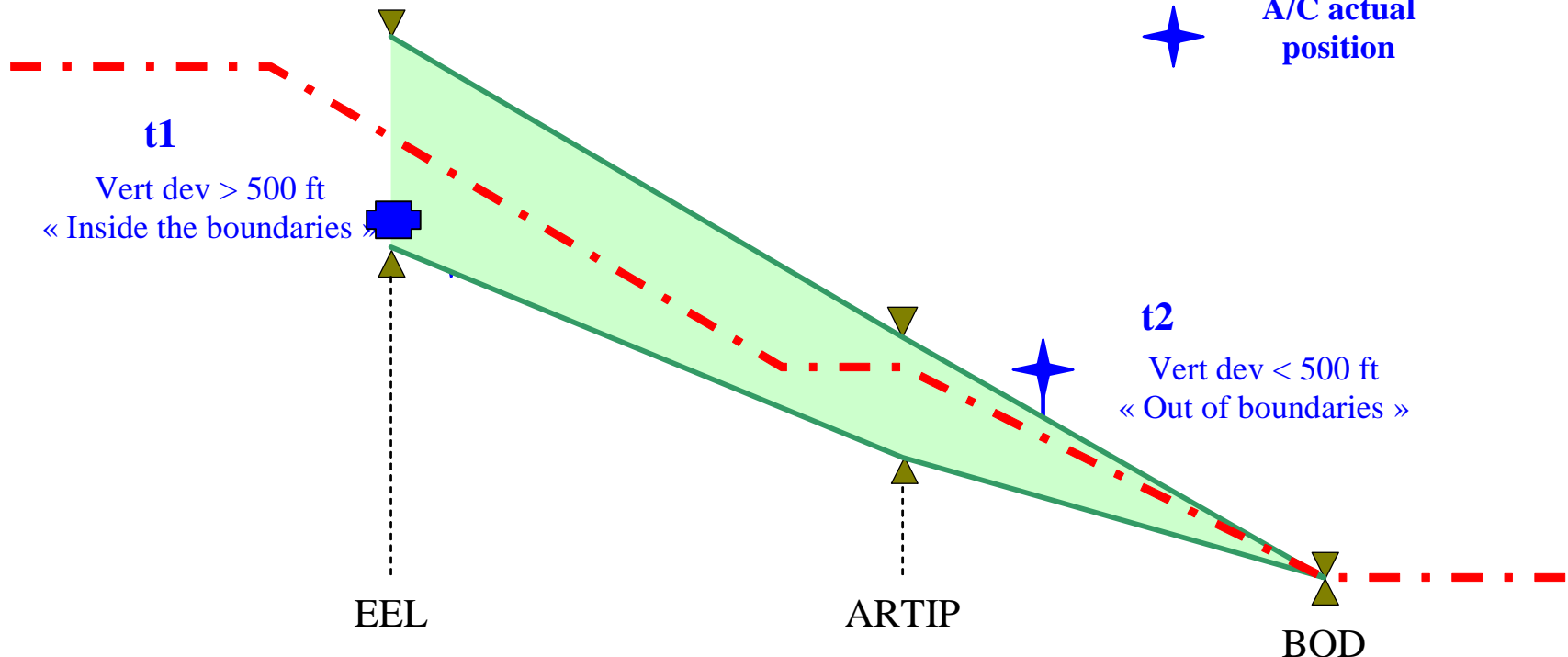
At t1 :  
- “out of boundaries” = NO  
- “vertical deviation” = YES

At t2 :  
- “out of boundaries” = YES  
- “vertical deviation” = NO

Vertical Boundaires  
(no deviation threshold)

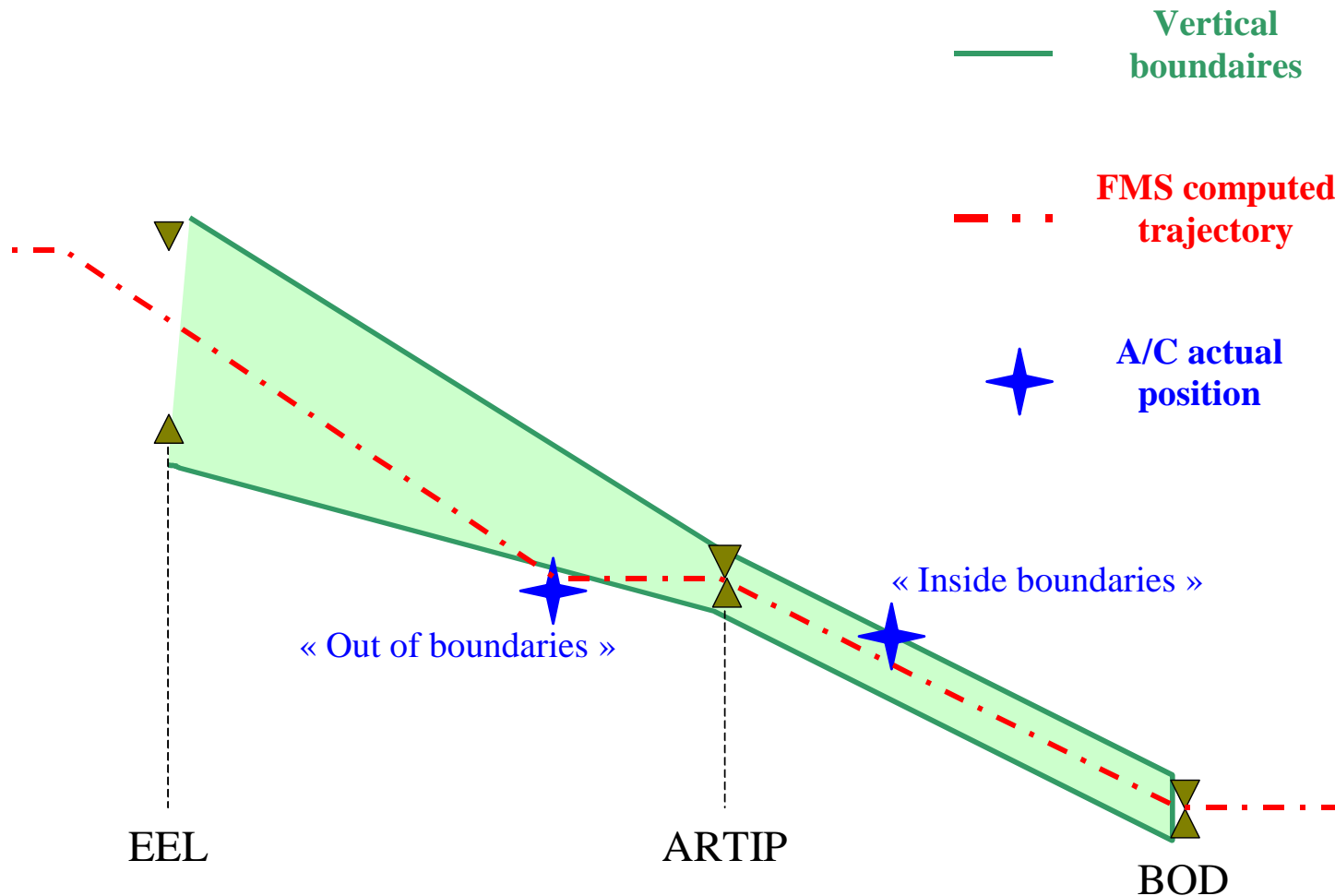
FMS computed  
trajectory

A/C actual  
position



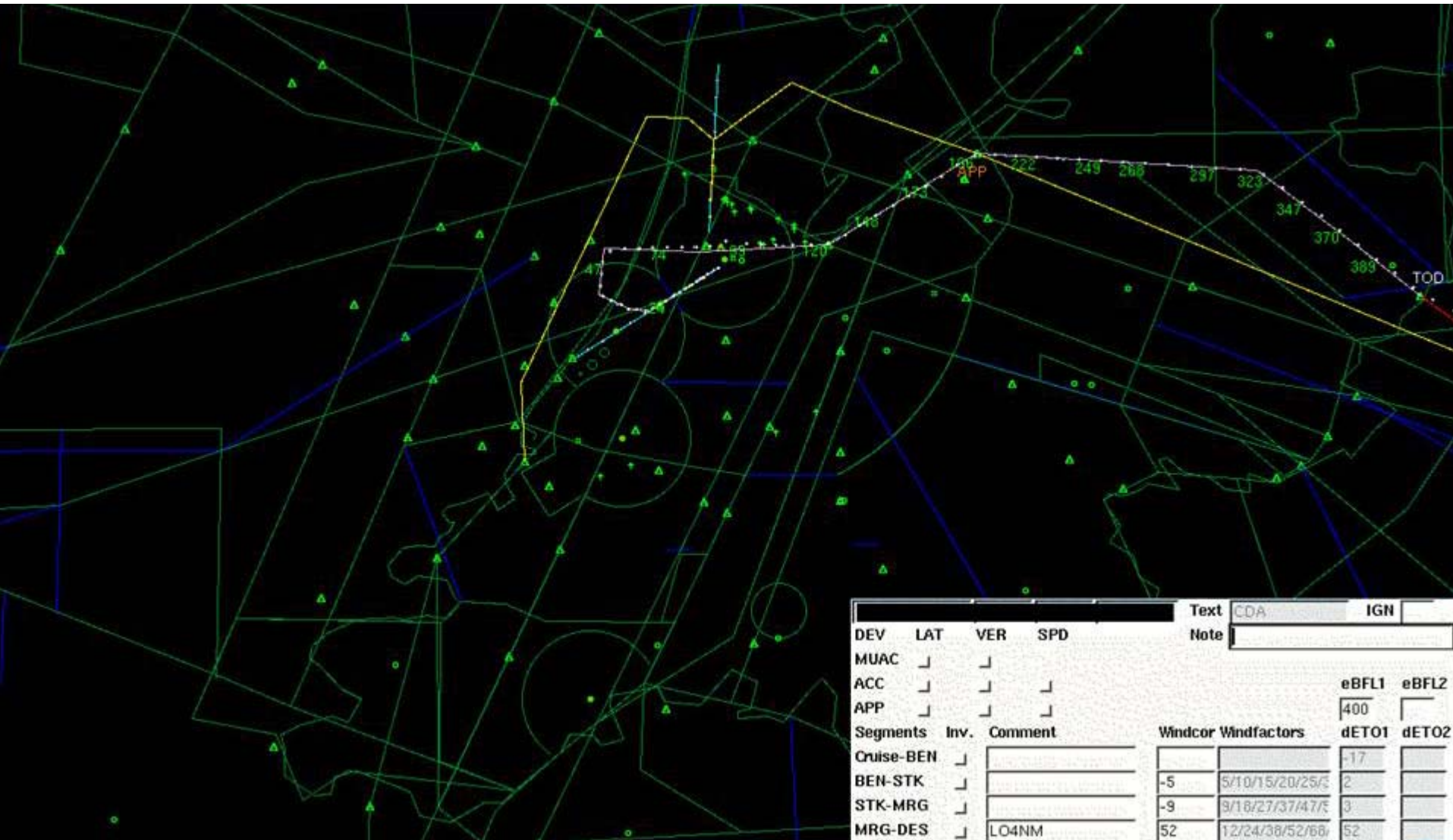
# Out of Vertical boundaries event contract

Engineering, Operations & Technology | Phantom Works



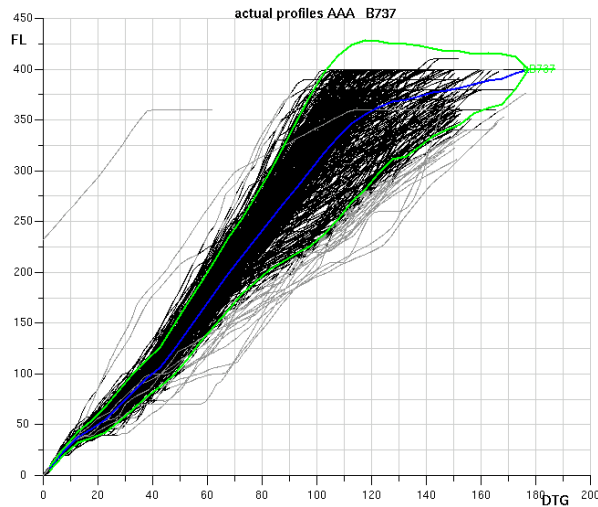


# Time Predictability

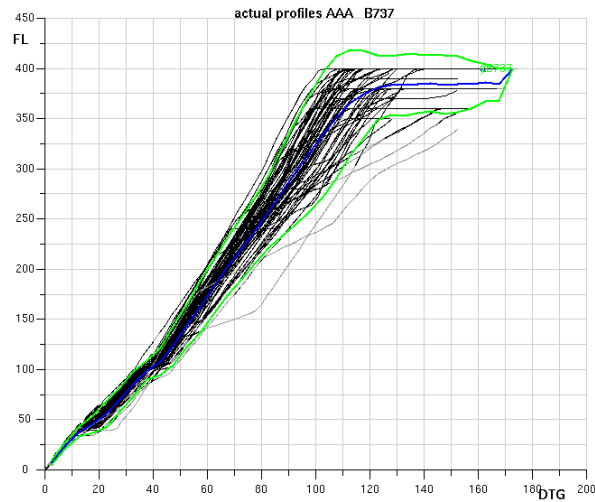


# Profile Predictability

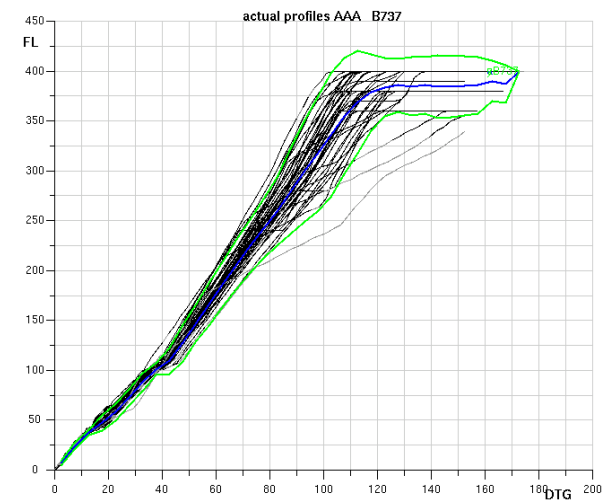
**All flights**



**Standard procedure**



**Refined procedure**



# Potential San Francisco Benefits

- Time and fuel savings based on TA vs. baseline scenarios with an 8,000-ft-level flight segment
- Baseline scenario with level segment of 5 nm representative of a low congestion period
- Baseline scenario with level segment of 20 nm representative of a congested period
- Pretrial assessment confirmed through simulator data and flight data

A/C	Fuel lbs	Time sec	Distance nm
747/2	392.8	37.0	5
20	782.5	73.7	10
	1,568.0	147.9	20
	3,123.0	296.5	40
757/2	77.0	42.5	5
20	154.0	85.0	10
	306.0	168.0	20
	612.0	336.0	40
767/2	135.2	34.7	5
40	270.4	69.4	10
	540.8	138.8	20
	1,081.6	277.6	40
777/2	192.0	36.8	5
40	384.0	73.6	10
	768.0	147.2	20
	1,536.0	294.4	40

# The key work areas

1. The ability to coordinate a clearance across multiple centers / sectors, and deliver it prior to TOD
  - Not a “technology issue”
  - Core to many advanced concepts, including 4D
2. Ground functionality that:
  - Produces sufficiently accurate a/c profiles to generate the clearances and constraints, using:
    - Sufficiently accurate a/c models
    - Up-to-date weather models
    - Sufficiently harmonized procedures
  - Uses these profiles to sequence and de-conflict a/c across the ATS Centers & Sectors involved